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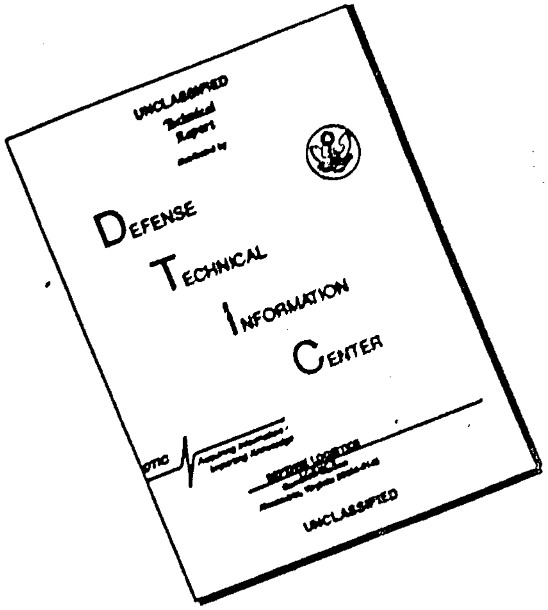

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A STUDY OF AN
INDUCTION-COUPLED PLASMA
OPERATING AT 400 KILOCYCLES

Howard R. Cannon

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A STUDY OF AN

INDUCTION-COUPLED PLASMA

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THESIS

Presented to the Faculty of the School of Engineering of

the Air Force Institute of Technology

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Master of Science

By

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Preface

This report concerns an elementary investigation of the problems of containing an induction-coupled plasma, measuring the plasma power and temperature, and determining the effects changing plasma operating conditions. I hope this report successfully establishes a starting point for future detailed investigations.

During the period of this study I was the guest of the Aeronautical Research Laboratories, and I wish to thank the members of ARL, who made my visit informative and enjoyable. My thanks particularly to the staff of the Thermomechanics Laboratory, ARL, for their support and encouragement.

I am especially indebted to E. Pfender for his guidance and support during his stay in this country, and to W. G. Braun and J. Birkeland, Plasma Physics Laboratory, ARL, for their explanation of Abel's Integral Transformation which appears in Appendix A. My thanks also to my lab partner, A. Shade, for the time and effort he devoted to assisting me, sometimes at the expense of his own study.

This report could not have been submitted in its present form without the patience and understanding of my Faculty Advisor, R. Wingerson. If time had permitted me to properly act upon his counsel, a far better report would have resulted.

And finally, my thanks to my wife, Carolyn, for her efforts to minimize distractions while I worked.

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D_c - Diameter of Radio Frequency Induction Coil

D_p - Diameter of the Plasma

E - Power Coupling Effectiveness

E_c - Calorimeter Power Coupling Effectiveness

E_r - Radiation Power Coupling Effectiveness

E_w - Wall Loss Power Coupling Effectiveness

E_t - Total Plasma Power Coupling Effectiveness

P_e - Plate Power-Excess

P_f - Plate Power-Filling

P_t - Plate Power-Total

R - Power Ratio

R_c - Calorimeter Power Ratio

R_r - Radiation Power Ratio

R_w - Wall Loss Power Ratio

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Abstract

A rf, electrodeless plasma-generator was developed which operated at peak plasma powers of 50 kw. The plasma was vortex stabilized, and was contained within a water-cooled Vycor tube. Power was measured calorimetrically. Radiation power was measured by alternately using clear water and water made opaque with India ink to cool the Vycor tube. A model temperature profile was deduced from spectrographic measurements transverse to the plasma axis. Maximum plasma temperatures were shown to exist in a thin cylindrical sheath near the plasma surface, with relatively cooler temperatures existing at the center-line gas back-flow. Effects of changing gas flowrate, gas composition, rf power, and Vycor tube diameter on the effectiveness of the energy coupling mechanism are shown.

A STUDY OF AN
INDUCTION-COUPLED PLASMA
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I. Introduction

An induction-coupled plasma is produced in a partially ionized gas by electrical currents which are inductively coupled to a radio frequency (rf) induction coil. This method of plasma production is capable of generating plasma free of the contamination which is characteristic of direct-current and alternating-current arcs. These arcs are contaminated by electrode erosion caused by the direct contact between the electrodes and the arc.

Induction-coupled plasmas are "electrodeless arcs" and there is no direct contact between the plasma and the rf power supply.

<u>Origin of the Study</u>

E. Pfender of the <u>Institut fuer Hochtemperaturforschung</u>, <u>Stuttgart-Degerloch</u>, Western Germany, initiated this study while he was engaged in research work at the USAF Aeronautical Research Laboratories (ARL), Wright-Patterson AFB, Ohio, at the suggestion of E. Soehngen, Chief of the Thermomechanics Laboratory, ARL. E. Pfender is interested in this plasma because it provides a possible source of electrons, ions, and neutral atoms which are in local thermal equilibrium (Ref. 7: 824), while E. Soehngen was primarily interested in the energy transfer characteristics exhibited by this plasma coupling mechanism.

Statement of Problem

The objectives of this study were (1) to operate a stable plasma at atmospheric pressure at 400 kilocycles (kc) with a sustained, high-power operation capability, (2) to determine the temperature profile of the plasma as a function of the plasma radius, T(r), (3) to measure the power transmitted to the plasma, and (4) to determine parameters important to the energy coupling mechanism.

Experimental approach

The plasma was contained in a water-cooled Vycor tube (Fig. 1), and was stabilized in the vortex flow resulting from tangential gas injection in the manner prescribed by T. B. Reed (Ref. 2: 822).

The temperature profile, T(r), was deduced from intensity profiles, N(x), of the lambda 7635AI and lambda 4806AII spectral lines obtained by spectrographic scans transverse to the plasma axis.

The total power transferred to the plasma was determined by measuring the power the plasma transferred to cooling water. Radiation power was measured by circulating an opaque coolant instead of clear water about the Vycor tube which contained the plasma (Fig. 2).

The parameters varied in this study were rf power delivered by the power supply, gas flow, the diameter of the Vycor tube containing the plasma, and the gas composition. The rf power was varied by changing the plate voltage of the power supply, and the gas composition was changed by mixing helium and argon.

<u>Possible Uses</u>

As stated by Reed, (Ref. 2: 824),

"It is still too early to say what the capabilities and limitations of inductive plasma generation are. We have used the plasma torch to grow single crystals of refractory oxides, and oxygen-containing plasmas will melt zirconium oxide (mp = 2700°C). The temperatures achieved in the plasma will depend ultimately on the power available and the nondestructive containment of the plasma. Presumably, the induction plasma will find use wherever the dc plasmas are used, from measurement of spectral transition probabilities to preheating gases for use in hypersonic wind tunnels."

In addition to preheating the gases for use in hypersonic wind tunnels, stagnation temperatures attainable in hypersonic wind tunnels can be increased by heat addition in the supersonic flow section using an induction-coupled plasma.

II. Experiment

Description of Apparatus

Part of the experimental apparatus is shown in Figure 3. In the background is the rf power supply. Starting at the extreme left, the apparatus seen is a portion of the gas supply bottle, the vacuum pump and vent, the vacuum pump shut-off valve, the exhaust valve, and the vacuum system pressure gages. The pressure gages are mounted on the support stand. Above the support stand the calorimeter jacket, plasma-generator, and the support stand scaffold are seen. Behind the calorimeter jacket two meters are seen, which were not pertinent to this study. The drape covers other equipment which was not pertinent.

Gas Supply System. The argon and helium used in this study were supplied by the Burdett Oxygen Company, and contained no more than one percent impurities by volume. Gas flows were measured by Airco Dual Range Flowmeters for Argon, style number 805-1601. These meters were calibrated from 1 to 106 standard cubic feet per hour (scfh). Gas flows in excess of 106 scfh were measured by using the meters in parallel. Helium flowrates were obtained from the argon flowmeter readings by use of conversion graphs furnished by Airco.

Plasma-Generator. The water-cooled plasma-generator was made in four pieces, the top and bottom end-pieces, and the inner and outer tubes (Fig. 4). The end-pieces were made of brass, the outer tube was Pyrex, and the inner tube was Vycor. Standard rubber O-rings coated with high vacuum silicone grease provided the seals between the end-pieces

and tubes.

The top end-piece contains the gas inlet, the gas injection plate, and the coolant outlet. In the gas injection plate are eight 0.055-in.-diameter holes equally spaced on a two-inch-diameter circle. The holes are inclined fifteen degrees to the face of the injection plate. As the gas enters the inner tube through these holes, the plasma-stabilizing vortex is formed. The coolant outlet is a piece of 3/8-in. copper tubing.

The bottom end-piece contains the hot-gas exhaust port, the coolant inlet, and the coolant manifold. The hot gases exhaust axially through a 7[illegible]-mm-diameter port, and a piece of 3/8-in. copper tubing provides the coolant inlet. The coolant enters and leaves the coolant manifold tangentially to prevent stagnation areas from forming in the coolant as it circulates between the inner and outer tubes. The coolant manifold was formed by machining a groove in the bottom end-piece. The coolant leaves the coolant manifold through the annulus formed by the inner tube and the 78-mm-diameter band that forms the top of the manifold. This narrow exit annulus (1.5-mm wide) shields the coolant between the tubes from the aspirator effect at the coolant inlet. This permits an upward spiralling flow pattern, free of stagnation areas, to exist between the tubes.

The tubes are mounted co-axially between the end-pieces. The inner tube is a Vycor tube 18-in. long with a nominal 75-mm outside diameter. Vycor was required because the inner tube must be capable of supporting a severe temperature gradient. On many occasions it was

observed that while the outer surface of the Vycor tube remained at water temperatures, the inner surface was glowing red hot. The outside diameter is listed as a nominal 75-mm because variations in this diameter of plus or minus one or two millimeters are common, and the tubes are often out-of-round. Because of these irregularities, the ends of the Vycor tubes most generally had to be sized before they were used.

The outer tube was a Pyrex tube [illegible]-in. long with a nominal outside diameter of [illegible]-mm. The outer tube carries the axial compressive loads which are applied to hold the plasma-generator together. The end-pieces are constructed in such a way that no axial compressive loads can be applied to the inner tube. This was done to prevent possible breakage of the inner tube by the combined effects of axial compression, thermal stresses, and hoop stresses caused by the pressure of the coolants.

Standard rubber O-rings were used to provide a seal between the end-pieces and the inner and outer tubes. Two O-rings were used at each seal to improve the reliability of the seal. Rubber gaskets were used to prevent direct contact between the ends of the tubes and the end-pieces to prevent chipping. The bottom end-piece is supported by the calorimeter and an O-ring provides the seal between these two parts.

<u>Calorimeter</u>. The calorimeter consists of a water-cooled jacket and two interior coils of copper tubing (Fig. 4). The water enters the outer shell of the jacket, flows up the outer shell, down the inner shell and then leaves the jacket. The cooling water next flows through the ascending coil of copper tubing, which is wrapped around the descending coil of copper tubing, and then through the descending coil and

out of the calorimeter. The coils of copper tubing were modifications made to existing equipment, and represent the simplest change that could be made. An existing joint in the exhaust pipe was separated and the cooling coils were inserted into the exhaust pipe. The cooling arrangement that resulted was not ideal, but it was adequate. The temperature of the exhaust gas was measured after the gas left the calorimeter, and the heat power remaining in the exhaust gases at this point was approximately 0.3 kilowatts (kw). After the gas leaves the calorimeter, it can be directed to the atmosphere or to a vacuum pump.

__Vacuum system__. The vacuum system used a vacuum pump constructed by Kinney Corporation, patent number [illegible]. This is a single-stage, rotary-vane, oil-sealed pump. This pump was capable of reducing the pressure in the plasma generator to 0.1-mm of mercury, absolute (mm Hg abs), under no-flow conditions.

Vacuum pressures were read on a vacuum pressure gage calibrated from 20-mm Hg abs to 0.1-mm Hg abs. The area of interest was below 1.0-mm Hg abs for if pressures this low were attained, it indicated satisfactory seals in the plasma-generator, and a start could be made. The plasma was not operated in a vacuum other than during starting. A second pressure gage in the system, which read pressures above and below atmospheric, in inches of mercury, was used to determine the appropriate time for opening the exhaust valve. The exhaust valve was opened when the pressure gage indicated atmospheric pressure.

<u>Coolant system</u>. The coolant system consisted of a coolant supply, the plasma-generator, the calorimeter, flowmeters, and connecting lines.

The primary coolant was tap water, but an alternate coolant supply was available for use in the plasma-generator. The alternate coolant was "black water" and was used to measure radiation power. The black water was a mixture of Carter's India Ink, tap water, and aqueous ammonia. The approximate proportions used were 30 gallons of water, three pints of India Ink, and one pint of ammonia. The ink was added to the water until the plasma was no longer visible through the plasma-generator, and the ammonia was added to prevent the ink from separating out of the water.

During operation, the black water was recirculated through a galvanized drum. Tap water which flowed through submerged cooling coils in the drum removed heat from the black water as it recirculated. The recirculating pump could deliver [illegible] pounds of water per hour at [illegible] psig, which was [illegible] pounds per hour less water and six psi less pressure than the tap water supply provided. The higher flowrate for tap water was used to inhibit nucleate boiling in the plasma-generator, because nucleate boiling leaves mineral deposits on the inner tube which interfer with radiation measurements.

Selector valves in the plasma-generator coolant lines permitted a shift to black water without the necessity of stopping the plasma. A bypass line was put in the black water system to permit operation of the recirculating pump at any time.

Coolant inlet pressure was monitored during the runs. In general, the black water pressure remained constant, but occasional high frequency fluctuations were noted. The tap water pressure was often varying up and down as much as two psi several times a minute.

Coolant flow to the plasma-generator was measured by four Fisher and Porter Stabl-Vis Rotameters in parallel, and water flow to the calorimeter was measured by a Fisher and Porter Flowrator. The Rotameters and Flowrator were accurate to the nearest five pounds per hour. The Rotameters could not be read when operating with black water, however, sufficient time was available between the time black water was selected and the time it reached the Rotameters to allow the new flow indication to stabilize and be read. Thereafter, the black water flow was considered constant, which appears to be a good assumption based upon the constant black water supply pressure.

Temperature Recording System. The temperature recording system consisted of Alumel-Chromel thermocouples, a cold junction, and a continuous recording galvanometer. The recording galvanometer used was a Honeywell Visicorder, Model 906C-1590H. The system was calibrated at ice bath temperature, boiling water temperature, and at 900°F and 1500°F. The system was linear over this temperature range, with an average response of [illegible]°F per inch. The Visicorder traced a ten-lines-per-inch scale on the tape, and the temperature traces were about 1/20-in. wide. The deflection of the center of the temperature trace was read to the nearest 1/40-in. Recordings were simultaneously made of the coolant inlet and outlet temperatures, and of the exhaust

gas temperature after the gas left the calorimeter.

<u>Support stand and scaffold</u>. The calorimeter was mounted in the support stand (Fig. 3). The calorimeter supported the bottom of the plasma-generator, and the support stand scaffold restrained the top of the plasma-generator. The restraining force applied to the top of the plasma-generator was necessary to hold the plasma-generator together because of the pressure of the coolant in the plasma-generator. The force on the top end-piece caused by this pressure was strong enough to cause the original wooden cross-bar of the scaffold to bend and thus allow the top end-piece to move. For this reason, an aluminum channel was used to reinforce the cross-bar, and then the restraining force was adjusted so that the top end-piece did not visibly move when the coolant was turned on. The outer tube of the plasma-generator is required to carry this load, and also the load resulting from the vacuum in the inner tube, before the coolant is turned on.

<u>Rf power supply</u>. The rf power supply was a Westinghouse power oscillator rated at 200 kw at 400 kc. The power output of this oscillator could be controlled by selecting one of the nine discreet plate voltages available, and then selecting a duty cycle. The plate voltage could not be changed while the power supply was operating, however, the duty cycle could be varied at any time from 0-100%. At duty cycles less than 100%, the rf power was delivered in pulses of varying lengths depending upon the duty cycle selected. The pulse rate was 360 per second. A duty cycle of 50%, then, resulted in pulse lengths of 1/720 second. A 100% duty cycle was used for this study, except during starting.

Experimental Procedures

The experimental procedures [illegible] be grouped into three categories. These three categories are (1) pre-starting checks, (2) starting procedures, and (3) data run procedures. The tasks covered under each category will be [illegible] of accom- plishment, [illegible] only those items which need [illegible] typical of [illegible].

Pre-starting Checks. [illegible] should be accom- plished [illegible] starting [illegible] safe operation of [illegible] [illegible] extra [illegible] reduces the power measured by the calorimeter.

If the vacuum [illegible] is satisfactory, the coolant system is turned on, and a check is made for leaks. Occasionally, water will seep into the inner tube even though the vacuum checked below 1.0-[illegible].

When this occurs, a [illegible] in the [illegible] usually [illegible] and ice will form where the water enters the inner tube. Small leaks of this nature can often be stopped by rotating the end-pieces and thereby resealing the O-rings. If this effort fails, it is necessary to disassemble the plasma-generator and change to O-rings of different sizes.

If no leaks are apparent, the coolant inlet pressure is raised to 40 psi, and the flowmeters are checked for normal readings. The flow to the plasma-generator torch will be approximately 2,400 pounds per hour, and the flow to the calorimeter will be about [illegible] pounds per hour. The calorimeter [illegible] in order to shorten the time required to reach temperature equilibrium.

No pressure or flow [illegible] in the [illegible] water system, but operation of this system can be checked by observing the sound of the recirculating pump, and observing the [illegible] action in the [illegible] through the bypass line.

After the coolant system exhibits proper operation, the [illegible] is slowly released and the torch end-piece is observed for [illegible] movement. Any movement of the [illegible] end-piece is [illegible] by [illegible] the restraining [illegible].

With the completion of the [illegible] tests, [illegible] and safe plasma operation are assured. However, the [illegible] should be checked for an hour's supply of recording tape, and the [illegible] should be checked for a supply pressure of approximately [illegible] psi to insure sufficient [illegible] for a data run.

Starting Procedure. The starting procedure is not included in the data run section because special attention should be given this critical portion of the plasma operation. The plasma is started in an argon atmosphere at an absolute pressure less than 1.0 mm Hg. Pressures near 1.0 mm are more desirable because starts may be obtained at lower rf power settings; this reduces the possibility of inner tube discoloration. Such discoloration can occur when the plasma touches the tube, as it does when operating at low pressures, if the rf power is too high.

When the starting pressure has been reached, the rf power supply is turned on, and the [illegible] is gradually increased until a pale pink glow is seen in the plasma-generator. At this time, the valve to the vacuum pump is turned off, because the pump is no longer needed and because this method leads to a more rapid pressure build up in the plasma. The gas supply valve is now turned on, and the pale pink glow turns into a brilliant blue white discharge. The next five to ten seconds is the most critical period of plasma operation. The flow is gradually increased to about 75 scfh, while the power is gradually increased to match the pressure rise associated with the gas flow. Should the power be increased too slowly, the plasma will extinguish; if the power is increased too rapidly, the plasma will contact the tube with sufficient energy to discolor it. This discoloration is permanent and precludes the use of the tube in radiation measurements.

The danger of discoloration rapidly decreases (due to plasma contraction) as the pressure and gas flow increase. As soon as the plasma contraction is noticed, the rf power may be increased fairly rapidly to a duty cycle setting of approximately 50%. Meanwhile, a close check on the plasma pressure is maintained, and as the pressure gage reaches zero psig, the exhaust valve is opened. When this task has been accomplished, the starting procedure is complete.

<u>Data Run</u>. The data run begins when the gas flow is increased to the maximum altitude of 25 scfh attainable, and the duty cycle is adjusted to 100%. The duty cycle remains on 100% for the remainder of the data run, while the gas flow is reduced in 25 scfh increments, until a flow of 100 scfh is reached. As soon as temperature equilibrium for each flow rate is indicated by the traces on the Visicorder tape, the tape is marked with the appropriate gas flow, and all meters are read. The meters read are the rf power supply plate voltmeter and plate ammeters, and all the water flowmeters.

A lower limit of 100 scfh on the gas flow was established because at flows less than 100 scfh, coolant boiling becomes substantial enough to cause mineral deposits to form on the inner tube, which interfere with radiation measurements.

After readings for a gas flow of 100 scfh are taken, the gas flow is increased to its maximum value as before, and the plasma-generator coolant supply is switched to black water. The coolant flowmeters must be read as soon as the coolant flow indications stabilize. There is

sufficient clear water in the coolant system ahead of the black water to allow the stabilized flow-indications to be read, before the flow indicators are obscured by the black water. The black water flowrate is assumed constant for the remainder of the data run. This assumption is reasonable since the black water supply pressure remains constant except for occasional indications of high frequency fluctuations of plus and minus 1/2 psi. The origin of these fluctuations is unknown, however, the fluctuations did not appear to effect coolant flowrate.

With the exception of the assumed constant values of black water flow, meter readings are obtained at 25 scfh flow increments as before. After the final set of readings are taken, the gas flow is increased to maximum value, and the duty cycle percentage is decreased, prior to turning off the rf power supply. This was done to cool the inner surface of the inner tube gradually enough to prevent post-operating tube cracks, which result from residual stresses caused by rapid cooling.

After the rf power supply was turned off, the clear water coolant supply was again selected, thereby flushing the black water from the coolant lines.

Physical Appearance of Plasma

The plasma first appears as a brilliant blue white discharge, in the vicinity of the rf induction coil, the instant the argon gas flow commences during the starting procedure. The plasma appears to extend out to the Vycor tube when operating at this low pressure. As the pressure and gas flow increase, the plasma contracts so that the

luminous gases no longer appear to contact the tube wall. The plasma is now shaped as a cylinder five to six inches in length and roughly centered in the rf coil area. This general shape is maintained until the gas flow approaches 60 scfh. At this gas flow, the top edge of the plasma intermittently extends up to the injection plate in the top end-piece. As the gas flow is increased to 70 scfh, the back-flow of gases up the center of the tube becomes strong enough to cause the top edge of the plasma to become permanently extended. The diameter of the extended portion of the plasma is largest level with the top of the rf coil, and is smallest at a point about two inches below the injection plate (Fig. 4). At this point the plasma begins to diverge toward the inlet holes in the injection plate. During the increases in gas flow, the bottom edge of the plasma extends downward slightly. Below the bottom coil, the brilliance of the plasma fades very sharply into a ragged-edged tail-flame approximately one inch long.

This description is representative of typical plasma operation. The dimensions of the plasma were not measured, and all stated values are approximations. Further, the dimensions of the plasma, and the gas flows at which plasma extention occurs are strongly dependent upon the rf power level. More important than the exact dimensions of the plasma are the changes in appearance of the plasma which result from changes in rf power and gas flow. Within the range of rf power and gas flow used in this study, increasing the rf power increases the diameter of the plasma and increases the length of the tail-flame, while increasing the gas flow decreases the diameter of the plasma, and increases

the length of the tail-flame. The changes due to changing rf power were observed by changing the duty cycle. After the rf power and gas flow were set for a data run any changes in the brilliance of the plasma were too subtle to be detected by eye. Due to the intense brightness of the plasma, it was normally observed through dark green glass.

Temperature Profile

A method for mapping the temperature profile of an argon plasma is explained by [illegible] (Ref. [illegible]). In brief, this method is based upon the temperature dependence of the normalized relative intensities of the atomic argon line lambda [illegible] and the ionic spectral line lambda [illegible] (Fig. [illegible]). The observed intensities of these lines along a diameter, N(x), is transformed into intensities which are functions of the radius, J(r), by the following integral (Appendix A). The prime indicates differentiation with respect to x.

$$J(r) = -\frac{1}{\pi}\int_{r}^{R} \frac{N'(x)\,dx}{\sqrt{x^2 - r^2}} \qquad (1)$$

Figure 6 shows the results obtained by inverting observed N(x)'s to radial distributions, J(r)'s using this integral, and then normalizing each curve with respect to its maximum intensity. This figure clearly shows that J(r) has a more pronounced dip at r equal zero, than does N(x) at x equal zero. The temperature profile, T(r), may now be plotted by taking the normalized relative intensity of one of the

spectral lines from Figure 6 for a particular radius, and obtaining the corresponding temperature from Figure 5. At this point, it is well to note that an ambiguity exists when using a single spectral line to determine temperature. With a normalized relative intensity of 0.85, it is possible to obtain values for temperature of either 14,000°K or 16,500°K. This ambiguity is solved by the presence of a measureable intensity of lambda 4806AII, which indicates temperatures above 15,000°K; or by the absence of this line, which indicates temperatures less than 15,000°K.

The investigation of the temperature profile of the plasma under study here is not complete. However, sufficient preliminary investigations were made to justify certain conclusions concerning the temperature distribution.

The intensity of lambda [illegible]AI, I(x), was recorded during runs using successively higher power levels. The recorded I(x)'s showed maximum values off the center-line (Fig. 7). The recorded maximum intensity and the center line intensities increased as a result of the first power increases. The power level was raised until successive increases in power produced no increase in the recorded maximum intensity. At this point the spread between the off-center intensity peaks began to increase, and the center-line intensity began to stabilize. These off-center peak intensities were now interpreted to be the location of the 15,000°K isotherm. Since the center-line intensities as I(x), were always less than the off-center maximums, even when these off-center

maxima could not be identified with the 15,000°K isotherm, it was concluded that the center temperature was less than 15,000°K. If, however, these low center-line intensities were indicative of temperatures above 15,000°K, the temperature would have to be in excess of [illegible]°K. At this temperature, the argon 4806 Å II line should show a strong intensity on the center-line provided the temperature did not exceed [illegible]. The presence of the argon 4806 Å II line was detected in the plasma, but only very faintly, and with a constant intensity across the plasma. This finding was interpreted as proving the existence of a temperature near 15,000°K in a very thin sheath near the edge of the plasma, and that the center-line temperature is less than 15,000°K.

These conclusions are compatible with two other proposed physical characteristics of this plasma. The first proposed characteristic is that skin effect causes the rf power to be transferred to the plasma in a cylindrical sheath in the area of highest electrical conductivity, which occurs in the area of maximum temperature. The second proposed characteristic is that the strong reverse gas flow in the center of the inner tube, caused by injection of the gas tangentially at high velocity, is modified only slightly by the presence of the plasma. The existence of strong back-flow through the center of the plasma precludes the existence of very high temperatures in this area because of the high viscosities exhibited by plasmas whose temperatures are above 15,000°K.

The plasma is pictured then as having its maximum temperature existing in a thin cylindrical sheath near the outer limit of the plasma, with a strong reverse flow of relatively cool gases up through the

center of the plasma. These findings are contrary to the findings of T. B. Reed who concluded that the highest temperatures exist at the plasma center (Ref. [illegible]: [illegible]23). The plasma investigated by Reed, was operated at a frequency of 4 megacycles at atmospheric pressure, using low gas flowrates, in a quartz tube with an inside diameter of [illegible] mm.

Operating Modes

The plasma was operated in four modes, as shown in Table I. As the study was originally conceived, Mode 1 was to be the standard mode for use in comparisons, and the other modes were to be different from Mode 1 in only one parameter. However, the plasma would not start in Mode 3 below a plate voltage setting of 10.1 kilovolts (kv); and plasma operation in Mode 4 was unreliable at a plate voltage of 7.6 kv, so the higher plate voltage was used. Mode 1 was chosen as the standard mode because operation in this mode was the simplest. Laboratory techniques used in this study resulted from the experience gained while operating in Mode 1.

Table I
Operating Modes

Mode	Plate Voltage (kv)	Gas (% by Volume)	Inner Tube Outside Diameter
1	7.6	100% A	75-mm
2	8.2	100% A	75-mm
3	10.1	100% A	45-mm
4	8.2	53% A 47% He	75-mm

Mode 2. Operation in Mode 2 was to show the effect of increasing the rf power available at a duty cycle of 10[illegible]. No particular difficulties were encountered during operation in this mode; however, power control, during starting, was more critical since the rf power output increased more rapidly with increasing duty cycle percentages in Mode 2 than it does in Mode 1.

Mode 3. Operation in Mode 3 was to show the effect of [illegible] the plasma in a small diameter tube, with the [illegible] all the same size. Operation in this mode is critical, because it is extremely difficult to start the plasma without [illegible] the inner tube. [illegible] in this mode [illegible] [illegible]-diameter outer tube, [illegible] that resulted [illegible] the inner tube. [illegible] outer tube was made [illegible] double diameter outer section, and no further [illegible] were experienced (Fig. [illegible]).

[illegible] differed from Modes 1 and 2 in that the [illegible] extended [illegible] injection into [illegible] also extended well down [illegible] rf coil, and [illegible] extended [illegible] into [illegible], [illegible] verified.

Mode 4. Operation in Mode 4 was to show the effect of diluting the [illegible] with helium. [illegible] dilution of [illegible] volume was desired, and operation with [illegible] dilution required a plate voltage of 8.2 kv to insure reliable operation. The mixture that was used in

this mode was approximately 47% helium by volume. The plasma was started in pure argon and the helium was introduced after the duty cycle had been adjusted to 100%. The appearance of the plasma which was 47% helium was not very different from the appearance of a pure argon plasma. However, if the percentage helium is markedly increased, the brilliance of the plasma decreases noticeably, and the [illegible].

III. Discussion of Data

The discussion of the data is presented here under three headings; data reduction, data presentation, and data accuracies. In this manner, it is hoped that the reader will gain a feel for the problems involved using the experimental techniques outlined in this study.

Data Reduction

The recorded data were in the form of volts, amperes, and flow rates. These data were first converted into power units, kilowatts, and then tabulated as shown in Table II.

Table II
Sample Power Measurements, Mode 3

Row	Gas Flow (scfh)	Q_w (kw)	Q_b (kw)	Q_c (kw)	P_t (kw)	P_i (kw)	P_e (kw)
1	175	9.14		3.93	147.0	120.0	27.0
2	175		12.98	4.02	152.8	120.0	32.8

The symbols used in the table are defined as follows:

Q_w - The power measured from the clear water used to cool the plasma-generator.

Q_b - The power measured from the black water used to cool the plasma-generator.

Q_c - The power measured from the cooling water in the calorimeter.

P_t - The plate power measured in the rf power supply when the plasma is operating.

P_i - The plate power measured in the rf power supply when the plasma is not operating, or idling plate power.

P_e - The excess plate power, which is the difference between P_t and P_i.

The first row of data was recorded during the clear water run and the second row recorded during the black water run. The difference in plate power between these two runs of 5.8 kw is larger than most differences recorded, but it serves to show the necessity of normalizing the data before any computation of the radial radiation power, Q_r, can be made.

The quantity Q_w is a measure of the power transferred to the walls by convection and that portion of the radiation absorbed by the clear water and the glass tubes. This portion of the radiation power was assumed negligible in comparison with either total radial radiation power, or convective power to the walls. The quantity Q_b is a measure of the sum of the power transferred to the walls by convection, Q_w, and the radial radiation power, Q_r. Q_r is radial radiation power that exists in the range of wavelengths for which Vycor, water, and Pyrex are transparent.

> Note: The quantity Q_r will hereafter be referred to simply as radiation power. It is in fact a measure of radial radiation only, as the axial radiation power is absorbed by the top end-piece of the plasma-generator and the calorimeter. No attempt was made to measure the axial radiation power, but it is included in the measurement of Q_w and Q_c.

If we therefore subtract Q_w from Q_b, the difference should be Q_r. From Table II, the value for Q_r thus computed would be 3.84 kw. Implied in this computation is the assumption that all the additional power measured with the black water was radiation power, and no consideration was given to fact that the rf plate power was 5.8 kw higher during the black water run. This increase in plate power reflects an increase in rf power output of something less than 5.8 kw due to normal losses in

the rf power supply. In turn, there would be an increase in power transferred to the gas somewhat less than the increased rf power output due to normal coupling inefficiencies between the rf coil and the plasma.

The problem, therefore, is determining how much of the 3.14 kw is due to radiation, and how much is due to the increase in rf power output. An approximate answer to this problem can be obtained by normalizing the calorimetry readings before subtraction.

The data were normalized with respect to P_i. Table III lists the values for P_i for the different plate voltage settings. When E_w, E_b, and E_c are divided by P_i, the quotient is a quasi-efficiency which will be called efficiencies, designated here as ϵ_w, ϵ_b, and ϵ_c, respectively. Values for ϵ_c are plotted in Figure 17. Table IV is the result of normalizing the data in Table II.

Table III
Idling Plate Power

Mode	Plate Voltage (kv)	P_i (kw)
1	7.6	62.0
2	8.[illegible]	77.0
3	10.1	120.0
4	8.2	77.0

Table IV
Sample Normalized Power, Mode 3

Gas Flow (scfh)	E_w (%)	E_b (%)	E_c (%)	E_r (%)	Q_r (kw)
175	33.8		14.55	5.8	1.57
175		39.6	12.25	5.8	1.90

E_r is taken as the difference between E_p and E_w, and is assumed to be unaffected by the different values of P_e. The validity of this assumption is open to doubt, but it appears to be a better first approximation than assuming that W_r remains constant during the increase in P_e. The values for W_r listed in Table IV are found by multiplying E_r by the appropriate P_e. This was done for the sake of comparison with the non-normalized value for W_r of 1.24 kw. It is also apparent from Table IV that two values for E_c can be obtained at each gas flow. Hereafter when a value is given E_c, whether it be in text, table, or graph, the value given will be the average of the two values of E_c for that gas flow. From Table IV, the value of E_c is 13.4% for a gas flow of 175 scfh.

The quasi-efficiency nature of the quantity E was mentioned, without discussion, before. E, as defined, is the percentage of excess plate power which goes to the plasma. The percentage of additional rf power which goes to the plasma would be of more interest to this study, but no means of measuring rf power was at hand. It is possible to say, however, that the amount of rf power available from this power source to operate the plasma is less than P_e, as it is not likely that all of this excess plate power is converted to rf power. Therefore, the values found for E will be conservative estimates of the coupling efficiency between the rf coil and the plasma. An item of interest, in addition to power conversion efficiencies, is the manner in which the power that goes to the plasma is distributed between the wall, radiation,

and the calorimeter. After E_w, E_r, and E_c are found, they can be summed to form a total effectiveness, E_t. Let the ratio of E_w, divided by E_t, be defined as R_w. Similarly, define R_r and R_c. These ratios show the distribution of power within the gas, as illustrated in Table V.

Table V
Sample Power Ratios, Mode 3

Gas Flow (scfh)	R_w (%)	R_r (%)	R_c (%)
175	63.8	10.9	25.3

Data Presentation

The data are presented in terms of the power coupling effectiveness, E, and the power distribution ratio, R, vs. gas flow in Figures 10 through 16. The points on the E_w, E_b, and E_c vs. gas flow graphs (Fig. 10 and 12) were obtained by normalizing P_w, P_b, and P_c with respect to P_e. The curves on these graphs represent the best fit to the data points by a second order (parabolic) curve. However, there is good argument for use of a third order (S-shaped) curves for E_b, Mode 2, and for E_w, Modes 2 and 3, based on the number of data points and their distribution. The type curve chosen to represent a series of data points should be based upon the exactness to which each data point can be located, as well as to the number and distribution of the points. If high confidence in the location of each data point is justified, a curve which closely fits all the data points can be drawn. If, however,

the possible variation in the exact location of a data point is large, then a lower order curve which tends to average out the point location uncertainties is more reasonable. The exact locations of the data points for E_w and E_b are not known with sufficient accuracy to justify more than a second order curve.

The feet attached to each end of these curves show the possible vertical displacements of the data points based upon the probable error in reading the coolant temperatures of plus or minus one degree Fahrenheit. These vertical displacements are essentially constant for all data points along that curve, and this display method was chosen over attaching the feet to each data point to prevent excessive cluttering of the graphs.

After the curves for E_b, E_w, and E_c were plotted, the difference between the E_b and E_w curves was drawn as the E_r curve (Fig. 11), and the sum of the E_b and E_c curves was drawn as the E_t curve (Fig. 13). The data dispersion which is inherent in the process of subtracting at each data point, and then plotting, is shown quite well in the plots of the data for E_r. The data points shown result from the subtraction of E_w data points from E_b data points. The subtraction technique will always produce this type of dispersion whenever the data are not perfectly smooth. The probable vertical displacement of points on the E_r curves was taken as $(2)^{1/2}$ times the average displacements for the E_b and E_w curves since these displacements are close to being equal.

The curves for R_w, R_r, and R_c result from dividing the E_w, E_r, and E_c curves by the E_t curve. In this manner, the normalizing quantity

P_e is eliminated, and the resulting quotients, Q_w/Q_t, Q_r/Q_t, and Q_c/Q_t, are the power distribution ratios, R_w, R_r, and R_c (Fig. 14, 15, and 16).

__Data Accuracies__

The only significant source of error in the data results from the low accuracy to which the coolant temperature rises can be determined. By reading the deflection of the center of the temperature trace to the nearest 1/40-in., the probable error in temperature measurement is approximately plus or minus one degree Fahrenheit. The following example illustrates the consequence of such an error.

For a typical coolant flow of 2500 pounds per hour, an error of plus or minus 0.732 kw may be expected in the value for Q_w. The resultant errors in E_w, from errors in power of this size, range from plus or minus 2.5% to plus or minus 0.9%. That is to say E_w equals 40% plus or minus 2.5%. For E_b, the errors due to inacurrate temperature measurement, range from plus or minus 2.2% to plus or minus 0.8%, which are slightly less than errors for E_w due to the lower black-water flowrate. The errors in E_r will contain the errors in E_w and E_b. Since the errors in E_w and E_b for a particular operating mode and gas flow are approximately equal, the error in E_r was taken as the $(2)^{1/2}$ times the numerical average of the errors for E_w and E_b. The range of errors thus computed for E_r are from plus or minus 3.3% to plus or minus 1.2%. Except for some variations in coolant flowrates, the errors in E_w, E_b, and E_r due to an error of plus or minus one degree Fahrenheit, are inversely proportional to the normalizing quantity, P_e. Other errors

result from the accuracy to which the coolant flowmeters, plate voltmeter, plate ammeters, and gas flowmeters can read, and from the failure to remove all of the power from the gas in the calorimeter.

The two plate ammeters can be read to the nearest 0.1 ampere, and the plate voltmeter can be read to the nearest 0.1 kv. The inherent error here is plus or minus 0.0035 kw which is insignificant when compared with the lowest value of P_e, which is 27 kw.

The Airco flowmeters are stated to be accurate within five percent, and they can be read to the nearest one scfh. It is assumed that any inaccuracies in the flowmeter are distributed over the whole range of the flowmeter. This type error will be shown as a scale error on the graphs, without appreciably changing the general appearance of the curves. The inaccuracy in reading the flowmeter would show as a horizontal displacement of a data point on the graph, however, a horizontal shift of one scfh would be hard to detect on the scale of 50 scfh per inch.

The largest amount of power remaining in the gas as it left the calorimeter was on the order of 0.03 kw. Had the calorimeter been totally effective, this power would add to Q_c. Since the smallest value for Q_c was 2.42 kw, the error in neglecting the power remaining in the gas is acceptable.

The water flowmeters could be read to the nearest five pounds per hour, or to within two and one-half pounds per hour. This error in coolant flow can lead to an error in power measurement up to 0.06 kw

depending upon the coolant temperature rise. The largest coolant temperature rises were in conjunction with power measurements on the order of 30 kw, so that this error is also negligible.

IV. Results and Conclusions

Before presenting the results and conclusions, it is necessary to fix in the mind of the reader exactly what was measured during this study, and what the purposes of the study were.

The quantities Q_w and Q_b represent the power transferred to the coolant as it passes through the plasma-generator. The quantity Q_c represents the power transferred to the coolant in the calorimeter.

Q_w is composed of three terms; a wall loss term, a radiation term, and a duct loss term. The wall loss is the power transferred by convection to the wall in the area of heat addition to the plasma. Since the plasma extends up to the injection plate, some wall loss is experienced there also. The radiation term is composed of the radiation absorbed by the coolant, the outer Pyrex tube, the inner Vycor tube, and the top and bottom end-pieces. The duct loss term represents power transferred to the wall which was available in the gas flow as enthalpy after the gas left the area of heat addition.

Q_b is composed of the same terms as Q_w with an additional radiation term. This additional term represents the radial radiation power absorbed by the black water.

Q_c is composed of two terms. The first term represents the power available in the gas flow as enthalpy after the gas leaves the plasma-generator. The second term represents the radiation from the plasma which is absorbed in the calorimeter. For the most part, this radiation

is axial radiation, but at high gas flow in small diameter tubes, the visible plasma could extend down into the calorimeter, in which case some radial radiation would also be measured.

The definitions for Q_r and Q_t need not be further expanded. Q_r remains the difference between Q_b and Q_w, and represents the difference between the total radial radiation and that portion of radial radiation which is absorbed by the plasma-generator, clear water, and the calorimeter should the plasma extend that far down. The total power transferred to the gas, Q_t, remains the sum of Q_b and Q_c.

The normalizing quantity, P_e, is the difference between a varying total rf power supply plate power, P_t, and the constant value of idling plate power, P_i. When a constant duty cycle is chosen, no control can be exerted on P_t, as the rf power supply automatically adjusts P_t in response to the load placed upon it. Since P_e differs from P_t by a constant, the variation of P_t with gas flowrate can be deduced from the plot of P_e vs. gas flow (Fig. 17). Refer to Table III for values of P_i.

The normalized quantities, E_w, E_r, and E_c represent a percentage of P_e, and therefore show how much of P_e was effectively transferred to the wall, to radiation, and to the calorimeter. When each of these characteristics is divided by their sum, E_t, the ratios R_w, R_r and R_c are obtained. These ratios show the percentage of the total power transferred to the plasma that goes to the wall, to radiation, and to the calorimeter.

In general, E_t did not vary greatly with gas flow (Fig. 13). Therefore, if either E_w, E_r, or E_c shows a strong variation, one or both of the other parameters must make compensating variations. Further, the relative constancy of E_t insures that increases or decreases in E_w, E_r, or E_c, are reflected by corresponding increases or decreases in R_w, R_r, or R_c. For this reason, the results and conclusions will be discussed in terms of E_w, E_r, E_c, and E_t only.

The objectives of this study were (1) to operate a stable plasma at atmospheric pressure at 400 kc with a sustained high-power operation capability, (2) to determine the temperature profile of the plasma as a function of the plasma radius, T(r), (3) to measure the power transmitted to the plasma, and (4) to determine parameters important to the energy coupling mechanism.

<u>Plasma Operation</u>

Using the techniques described in this study, a stable plasma was operated at 400 kc at atmospheric pressure. No endurance runs were made, however, the plasma has been continuously operated for forty minutes during some data runs which included peak plasma powers up to 52 kw. With a modified injection plate to prevent injection plate damage, and heat resistant seals to prevent seal deterioration, the plasma is believed capable of continuous operation at the 50 kw power level at gas flows above 100 scfh, in a 75-mm Vycor tube. Stable operation of the plasma was concluded on the basis of apparent constant plasma geometry, and stationary values of coolant temperature indications during operation at constant gas flow.

Temperature Profile

Although temperature profile measurements were not complete, the existence of a temperature of 15,000°K near the outer surface of the plasma was verified, and a model temperature profile was deduced. The deduced temperature profile shows the highest temperatures occuring in a thin cylindrical shell near the outer surface of the plasma, and relatively cooler center-line temperatures existing in a reverse gas flow.

Power Measurements

The techniques used to measure power were only partially successful. The margin for error in determining the coolant temperature rise was unacceptable for so critical a measurement. This fault coupled with the shift in P_e between the clear water and black water runs, led to excessive data dispersion which in turn prevented obtaining point-by-point radiation power values by subtraction of the point values for Q_w and Q_b. Q_w and Q_b were normalized with respect to P_e and the results plotted as E_w and E_b vs. gas flow in scfh. A smooth curve for E_w was then drawn and subtracted from the smooth curve drawn for E_b. This yielded smooth curves for normalized radial radiation power, E_r. The usefulness of radiation values obtained in this manner rests on the validity of the averaging processes inherent in normalizing data and plotting smooth curves. In consideration of the limitations imposed by possible data accuracies and experimental techniques used in this study, the information displayed on all graphs should be viewed as

first approximations of actual values and trends.

The black water technique as applied in this study is very useful as a means of determining total plasma power. Better measurements of radiation power would be possible with the use of an improved black water which did not leave deposits on the inner tube. This innovation is discussed under "Recommendations". With the use of an improved black water, this technique of measuring radiation power should yield usable radiation power data without the necessity of first normalizing the data.

Coupling Parameters

The controlled parameters were rf power supply plate voltage, inner Vycor tube diameter, gas composition, and gas flow, however, other implicit parameters were present. The implicit parameters appearing in this study are plasma pressure, vortex strength, rf power supply plate power, and plasma length and diameter. No control can be exerted over these parameters, as they are the natural consequences of varying the controlled parameters.

Conclusions concerning a coupling parameter must be supported by a reasonable quantity of data pertinent to the effects of that parameter. The preponderance of information gathered in this study directly concerned gas flow. For this reason, the effects of varying gas flow are well described. The effects of varying gas composition, inner tube diameter, and plate voltage cannot be described nearly as well due to the meager investigations made of each of these parameters.

Direct comparisons of the operating modes which contain these parameters as variables can establish a trend which would have some short range validity, but any long range projections made on the basis of these limited comparisons are of doubtful validity.

Gas Flow. The effect of increasing gas flow on all operating modes is similar, but somewhat varying in degree. For instance, a sharp decrease in E_w is noticed with an increase in gas flow for Modes 1, 2, and 3; but Mode 4 exhibits only a slight decrease in E_w. In general, the decrease in wall loss and radiation characteristics and the increase in the calorimeter characteristics with increasing gas flow can be attributed to the decrease in plasma diameter which occurs with increasing gas flow. Some lengthening of the plasma tail-flame is also noted with increased gas flow, but no significant increase in length of the highly luminous portion of the plasma was observed. As the plasma contracts, at high gas flows, wall losses are inhibited by the increased separation between the plasma and the walls, and the effective volume of radiating plasma is decreased, thereby reducing radiation losses. The reduction in radiating volume apparently offsets any tendency to increase radiation power through possible increased plasma temperatures. In the absence of temperature measurements to the contrary, it is believed that plasma temperature very likely decreases with the increasing gas flow due to the decrease in energy coupling to the restricted plasma volume.

The reduction of wall losses and radiation losses at higher gas

flows is reflected by an increase in power carried to the calorimeter by the flowing gases.

Gas Composition. The only gas used other than argon was a mixture of argon and helium. The mixture used was approximately 47% helium by volume, or about 8.9% helium by weight. This dilution of pure argon led to marked differences between the results of Mode 4 and Mode 2. The increase in wall loss characteristics and the decrease in radiation loss characteristics are respectively believed to be the result of the higher thermal conductivity and lower emissivity of helium. The calorimeter characteristics for these two modes are nearly equal, which suggests that the decreased radiation losses were offset by equivalent increases in wall losses.

Plate Voltage. The effects of increasing plate voltage appear in the comparison of Modes 1 and 2. The changes experienced by raising the plate voltage were the least predictable of all changes resulting from varying the other parameters. It was earlier observed that an increase in rf power output increased the diameter of the plasma. During any data run it was also observed that as the diameter of the plasma increased E_t increased. These two bits of information seemed to point the way toward an increased coupling effectiveness at higher plate voltage settings. It was predicted that the higher rf power output, which would accompany the higher plate voltage setting, would increase the plasma diameter which would in turn increase E_t. The effect on E_t was just the opposite; E_t decreased. Q_w, Q_r, and Q_t, however, increased in Mode 2, but these increases were obtained at relatively higher increases

in P_e, so that E_r, E_w, and E_t decreased in Mode 2. The most unexpected result was that Q_c for Mode 2 was less than Q_c for Mode 1, for an increase in all power measurements was expected because of the increased rf power output.

No explanation of the decrease in E_t is offered. An examination of Figure 8 shows a decrease in electrical conductivity of an argon plasma at temperatures from 22,000°K to 25,000°K. A decrease in conductivity of the plasma could account for the decrease in E_t, but the existence of temperatures on the order of 22,000°K is ruled unlikely, although a temperature profile at this power level was not attempted. The decrease in Q_c is possibly due to increased energy losses to the wall since the highest gas temperatures occurred closer to the walls. Further study is needed to clarify the apparent contradictions that occurred during Mode 2 operation.

<u>Inner Tube Diameter</u>. The variations in plasma characteristics resulting from using a smaller diameter inner tube in Mode 3, show the effects of constricting the plasma, and thereby reducing the energy coupling and the effective radiation volume of the plasma, and the effect of the close approach to the wall by the plasma. The total effective coupling is low due to reduced energy coupling. The radiation characteristics are low due to the small radiation volume and probable lower plasma temperature, and the wall loss characteristics are high due to the close proximity of the plasma to the wall. The calorimeter characteristics are also noted to be high, but these values

are questionable. The possibility that the plasma extended down into the calorimeter during Mode 3 operation was previously mentioned. This event would result in measuring a certain amount of radial radiation in the calorimeter, and suggests that the values shown for the calorimeter characteristics are too high, and that the values shown for radiation characteristics accordingly are too low.

V. Recommendations

General

The conclusions presented here were based on a study which just scratched the surface of the research needed for the proper understanding of the phenomena of the induction-coupled plasma. These conclusions represent the best that the present investigation has to offer.

The main areas for improvement and continued study brought out by this study are (1) the plasma-generator, (2) the coolant temperature measurement, (3) plasma temperature measurement, and (4) radiation power measurements.

An additional parameter which is available through the use of the duty cycle control on the rf power supply should be studied. Duty cycles less than 100% would have an important bearing on the efficiency of an induction-coupled plasma used as a gas heater.

Plasma-Generator

Gas Injection Plate. The present gas injection plate with eight injection holes on a two-inch diameter circle offers no flexibility to gas injection, and the center of the plate is subjected to severe heating at high power operation. To add flexibility to gas injection, it is recommended that the injection system use two sets of injection holes drilled on different diameters. Each set of holes would be of different size and be supplied gas through independent gas manifolds.

This arrangement would allow the selection of different vortex strengths at the same total gas flow. In this manner, the effects of vortex strength could be shown. The results of this experiment could be presented as illustrated in Figure 17. The curves would be lines of constant gas flow. The left most point would represent 100% of the gas issuing from the manifold with the larger holes, and the right most point would represent 100% of the gas issuing from the manifold with the smaller holes.

A method for eliminating the heat loads on the injection plate was suggested by E. Soehngen. He suggested that a small amount of gas injected axially from the center of the injection plate would prevent the plasma from contacting the plate. As an extention of this idea, it might very well be possible to accurately position the top of the plasma by varying the axial gas injection which would control the reverse gas flow. Preventing the plasma from contacting the injection plate will allow operation at higher powers without contamination of the plasma by material from the injection plate.

<u>Tube Diameters</u>. The manner in which the power coupling increases as the plasma expands suggests that the ratio of plasma diameter over rf coil diameter (D_p/D_c) is a parameter which should be studied. Studies should be made using larger diameter tubes, but keeping the same waterjacket thickness, or possibly reducing the waterjacket thickness, in order to increase D_p/D_c.

<u>Starter Mechanism</u>. A large percentage of tube damage and breakage that occurred during this study could be directly attributed to "hot starts" using the vacuum start technique. T. B. Reed used an inductively heated graphite rod or refractory wire loop to start the plasma at atmospheric pressure (Ref. [illegible]). The breakdown potential of the gases heated by this means was lowered sufficiently to allow ignition of the plasma by the rf field. Starting the plasma at atmospheric pressure would prevent the tube damage experienced during vacuum starts, and would also eliminate the need for a vacuum system. A means of inserting and withdrawing a carbon rod or refractory wire loop through the [illegible] could be devised for starting purposes.

<u>Seals</u>. Seals for the inner and outer tubes were provided by standard O-rings. The O-rings at the bottom of the inner tube are subjected to severe heating, and cannot be reused. The O-rings are heated by conduction and radiation from the hot Vycor tube. Should the plasma extinguish after more than a few minutes at high power, these bottom seals almost certainly will have to be replaced before a sufficient vacuum for a re-start can be reached. The higher temperature capabilities of silicone rubber suggests that O-rings made of white silicone rubber might solve, or at least ease, this problem.

<u>Waterjacket</u>. The space between the inner and outer tubes for a large part determines the water flow necessary to prevent local boiling next to the inner tube. Reducing this space, by proper selection of tube diameters, leads to smaller water flow requirements for the purpose of reducing local boiling. Reducing the water flow in turn reduces

the error in power measurements due to water temperature determination accuracy. If the waterjacket is made too thin, however, the black water technique for total power measurement may not be effective. In general though, smaller water flowrates, and higher temperature rises lead to better accuracies for power measurements, and therefore, a thin waterjacket should be considered.

Coolant Temperature Measurements

Coolant temperature measurements are very critical to power measurements, especially at high coolant flows. Temperature measurements accurate to the nearest one-half degree Fahrenheit would more nearly align the magnitude of error in power measurements resulting from temperature inaccuracies to the magnitude of error resulting from water flow inaccuracies. Reducing temperature inaccuracies beyond this point will yield little in overall accuracy, and therefore become luxuries. At the least, temperature measurements should be accurate to the nearest degree Fahrenheit.

Plasma Temperature Measurements

An accurate knowledge of the temperature profile of an induction-coupled plasma is essential to the understanding of the basic phenomenon of induction-coupled plasmas, and to the development of theories to explain this phenomenon.

At present, W. G. Braun of the Physics Branch, Aeronautical Research Laboratory, and C. Grabner, Chief of Analysis Branch, Digital Computation Division, Aeronautical Systems Division, are developing a

computer program which will yield a spectral line intensity profile, $J(r)$, from an observed $N(x)$. The computer program will be applicable to any measurements for which axial symmetry can be assumed. When the program is established, the computer will fit an even ordered polynomial ($a_0 + a_2x^2 + a_4x^4 + \ldots + a_{2n}x^{2n}$) to the observed data to obtain an analytical expression for $N(x)$. It will then differentiate $N(x)$ with respect to x, substitute $N'(x)$ into the integral equation, Eq (1), and perform the integration to obtain $J(r)$.

When this valuable tool is available to make multiple temperature profile determinations practical, a series of test runs in the pattern of this study should be made to determine the parameters which effect the maximum temperatures attainable, and the radius at which these maximum temperatures occur.

Radiation Power Measurements

Radiation power measurements in this study were hindered by two basic faults, other than inaccurate temperature measurements. The time difference between the clear water and black water readings is one fault, and the other fault is the inability to reproduce the plasma, as evidenced by the different values of I_c which occur at the same gas flow during the same data run. Ideally, all measurements are made simultaneously so that there is no time difference and no non-reproducibility problem.

Since plasma power is not time dependent while operating at a constant gas flow, measurements can be made at different times and still be valid if they do not depend upon reproducibility. This condition is satisfied by leaving the gas flow constant and switching the coolant supply between clear and black water to get measurements of both q_w and q_b. However, the black water used in this study deposited on the inner tube, and no clear water measurements could be taken after black water was once used. Therefore, an opaque coolant which does not deposit on the inner tube should be found for use in this radiation measurement technique.

A possible method for obtaining simultaneous power measurements was suggested by R. Wingerson, Physics Department, Air Force Institute of Technology. He proposed that the amount of radiation falling on a radiometer at some fixed distance from the plasma should be compared with the radiation measurements made by switching to black water without changing gas flow, to determine if the two radiation measurements are in some manner proportional. Using the present black water supply, this method entails cleaning the plasma-generator, between test runs. If a proportionality exists, then the radiometer should be carefully calibrated by a series of runs, so that subsequent radiation measurements can be made using the radiometer. The ability to obtain simultaneous power data is well worth the effort to calibrate the radiometer, therefore, tests for proportionality should be made.

Energy Balance

An energy balance on the plasma was not performed because no measurements of total electrical power transferred to the plasma could be made. There is a relatively simple method available to measure the electrical power absorbed by the plasma, but it requires additional instrumentation on the rf power supply. This method was suggested by Taylor and Hastings (Ref. 3: 1371). The additional instrumentation required is an rf ammeter in the circuit with the rf induction coil, and water flowmeters and thermocouples in the cooling system for the triodes in the rf power supply.

The total electrical energy supplied to the triodes can be measured with direct-current meters. The energy lost in the triodes is given off as heat and can be measured by reference to cooling water temperature rise and water flow. The energy not lost in the triodes is converted to rf energy output.

To obtain a measure of rf energy transferred to the plasma, the power supply is first operated in the absence of a plasma at some set value of rf current on the rf ammeter in the induction coil circuit. Total electrical energy to the triodes and total triode losses are then measured as previously explained. The difference between these values is the rf energy losses which occur at that rf current. The power supply is next operated in the presence of a plasma, at the same rf current. The total triode energy input and losses are measured as before. The rf energy losses at this rf current were previously determined. The rf energy losses are added to the triode losses which

occurred on the second run, and this sum is then subtracted from the total energy supplied to the triodes on the second run. This difference is the energy which is transferred to the plasma.

By knowing the rf energy supplied to the plasma, a proper energy balance can be made. An energy balance is deemed necessary to validate the measurements made on the plasma by the techniques used in this study.

Supersonic Heating

The possibility of adding heat to the air in the supersonic region of a hypersonic wind tunnel by a rf induction-coupled plasma, was mentioned in the introduction. However, plasma operation in gases with high linear velocities is unstable because the plasma cannot propagate fast enough upstream. In the vortex-stabilized plasma, ionized gas is blown upstream by the back-flow. This feedback system continuously supplies the ions necessary to maintain coupling between the rf induction coil and the plasma.

Stabilization by vortex flow in hypersonic wind tunnels cannot be considered, because it disrupts the gas flow. A schematic presentation of a stabilization scheme is shown in Figure 19. This scheme invisions a constant supply of electrons being injected into the gas flow near the throat of the wind tunnel. These electrons are carried downstream, by the fast moving gases, into the plasma coupling area where they couple with the rf induction coil, and thereby stabilize the plasma. As the electrons move downstream past the plasma area they are returned to ground, leaving a neutral gas behind.

The electrons can be generated in a typical electrohydrodynamic ion-production method. For negative ion production, the corona discharge needle is given a high negative charge, just short of breakdown potential. The positive ions created near the needle point are attracted to the needle, whereas the negative ions are attracted to the nearby ground. Before the electrons can reach ground, however, they are carried downstream through the plasma discharge area by the gas stream.

This stabilization scheme seems feasible. There is no doubt that the negative-ion stream can be generated; but only experimentation will show if this ion stream will couple with the induction coil, and if the plasma thereby generated can be confined to a volume small enough to prevent destruction of the tunnel walls. If coupling occurs without damage to the tunnel walls, the usefulness of this heat addition method is limited only to the extent to which the plasma experiences a braking effect caused by interaction between induction currents in the plasma and the field of the rf coil.

This heat addition system in the supersonic flow section of a hypersonic wind tunnel appears feasible, and should be checked by experimental means.

Duty Cycle as a Parameter

A duty cycle control on the rf power supply allows selection of any duty cycle desired between 0% and 100%. For any particular plate voltage setting, this allows selection of any plate power from zero to the maximum attainable on that plate voltage setting. Consequently,

with a prior knowledge of idling plate power, P_i, for that plate voltage setting, a particular value of P_e can be selected exactly by use of the duty cycle control.

When the rf power supply is operated at a duty cycle less than 100%, the rf power is emitted in pulses at the rate of 360 per second. The duty cycle percentage corresponds to the length of these pulses. A duty cycle of 36%, for example, yields power pulses whose duration are 0.001 second, and which occur at a rate of 360 per second. During any second then, the rf power is emitted for 0.36 second.

The pulsing nature of this power supply could conceivably have important implications in the use of an inductively-coupled plasma as a gas heater, such as heating gases for wind tunnels. One of the characteristics of plasmas, such as found in a direct-current arc, is that they are so viscous they defy efforts to blow gases through the arc channel. This limits the effectiveness of heating gases by electric arcs. This shortcoming of arcs can be circumvented in a pulsed induction-coupled plasma, because instead of relying upon heating the cold gases by moving them through the plasma, the plasma propagates through the cold gases. High speed photographs taken of a plasma operating at a duty cycle of 50% clearly show the pulsing nature of the plasma. When the power pulse ends the plasma periphery cools rapidly, and the radiating plasma gradually shrinks toward the center of the tube. When the next power pulse occurs, it couples with the remaining conducting gas, and the plasma gradually swells to normal size. The pulsing of the plasma is not visible to the eye, and normal size refers

to the size of the plasma seen by the eye. It is proposed that this pulsing action of the plasma more effectively heats the gas than operation of the plasma at a duty cycle of 100% , because wall losses and radiation should decrease due to pulsing the power. A series of tests should be run at the same gas flow and P_e on the nine possible plate voltage settings to confirm or deny this proposal.

Summary

Very little information is available on induction-coupled plasmas to date. This study is the only work known to the author which is available on induction-coupled plasmas operating below the megacycle range. The rf power supply used in this study is versatile enough to tax the ingenuity of the investigator to use it. It is probable that sufficient power is available to investigate plasmas in pure gases other than argon at atmospheric pressure, if a plasma-generator is developed to contain it. The studies which could be conducted on induction-coupled plasmas are so numerous that it would be desirable to outline a systematic, long term program of investigation. This study has established the general characteristics of a high-power induction-coupled plasma-generator, and has revealed a number of experimental difficulties which must be considered. Thus a comprehensive program of investigation may now be confidently undertaken.

Bibliography

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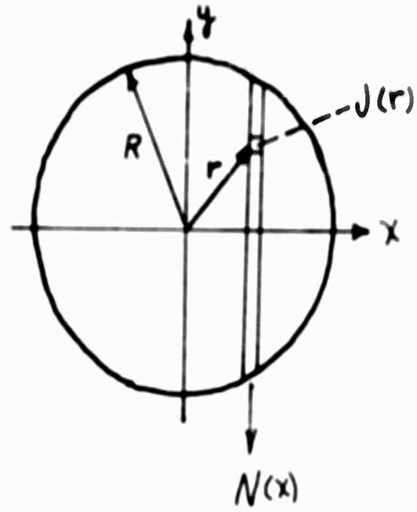
Appendix A

Abel's Integral Transformation

The transversally observed radiance of the plasma image, N(x), is inverted to the radiant intensity, J(r), in the following manner.



$$N(x) = 2\int_0^y J(r)\,dy$$

But,

$$y = \sqrt{r^2 - x^2}$$

And,

$$dy = \frac{r\,dr}{\sqrt{r^2 - x^2}}$$

Therefore:

$$N(x) = 2\int_x^R \frac{J(r)\,r\,dr}{\sqrt{r^2 - x^2}}$$

This is Abel's integral, which inverts analytically to form

$$J(r) = -\frac{1}{\pi}\int_r^R \frac{N'(x)\,dx}{\sqrt{x^2 - r^2}}$$

The prime indicates differentiation with respect to x.

Figures

GA/Phys/62-2

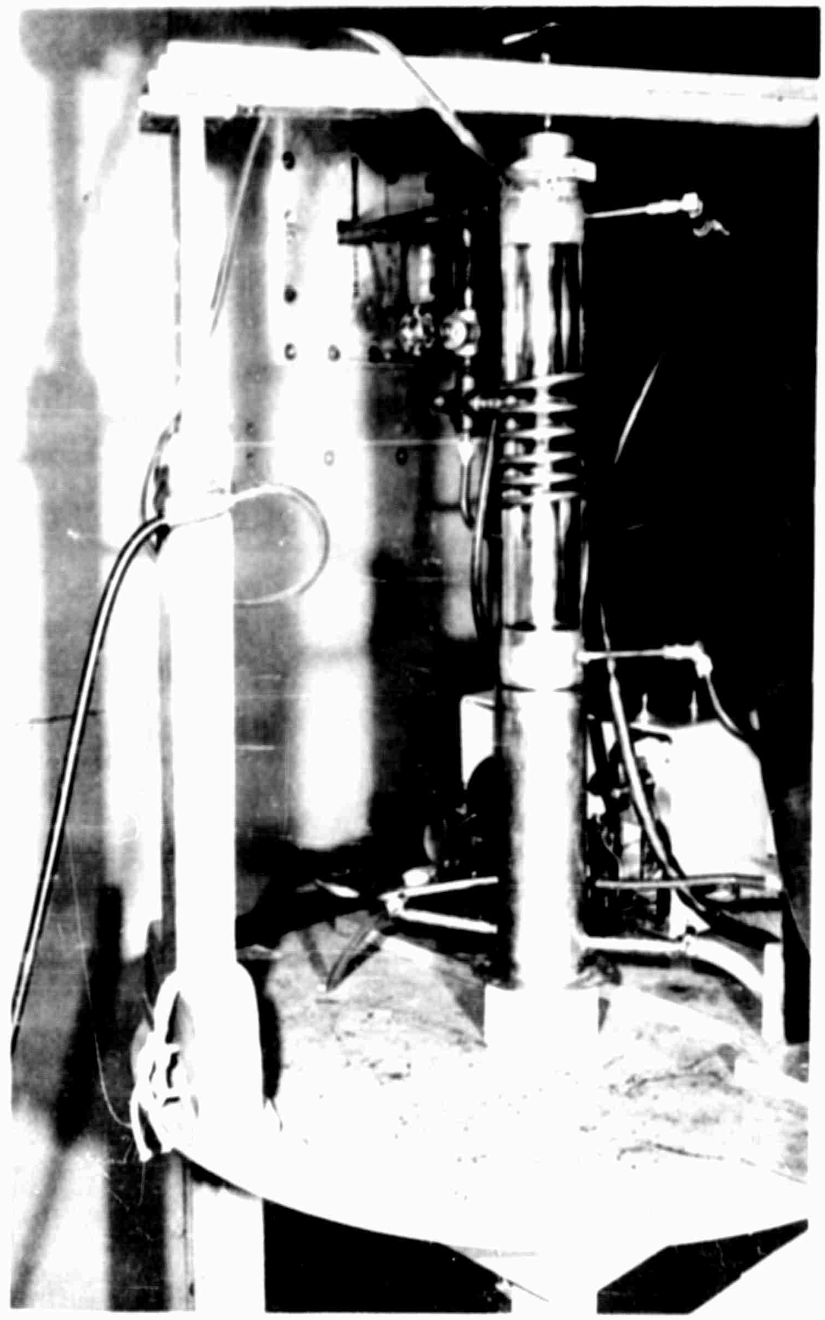


Fig. 1

Plasma-generator with clear water coolant

GA/Phys/62-2

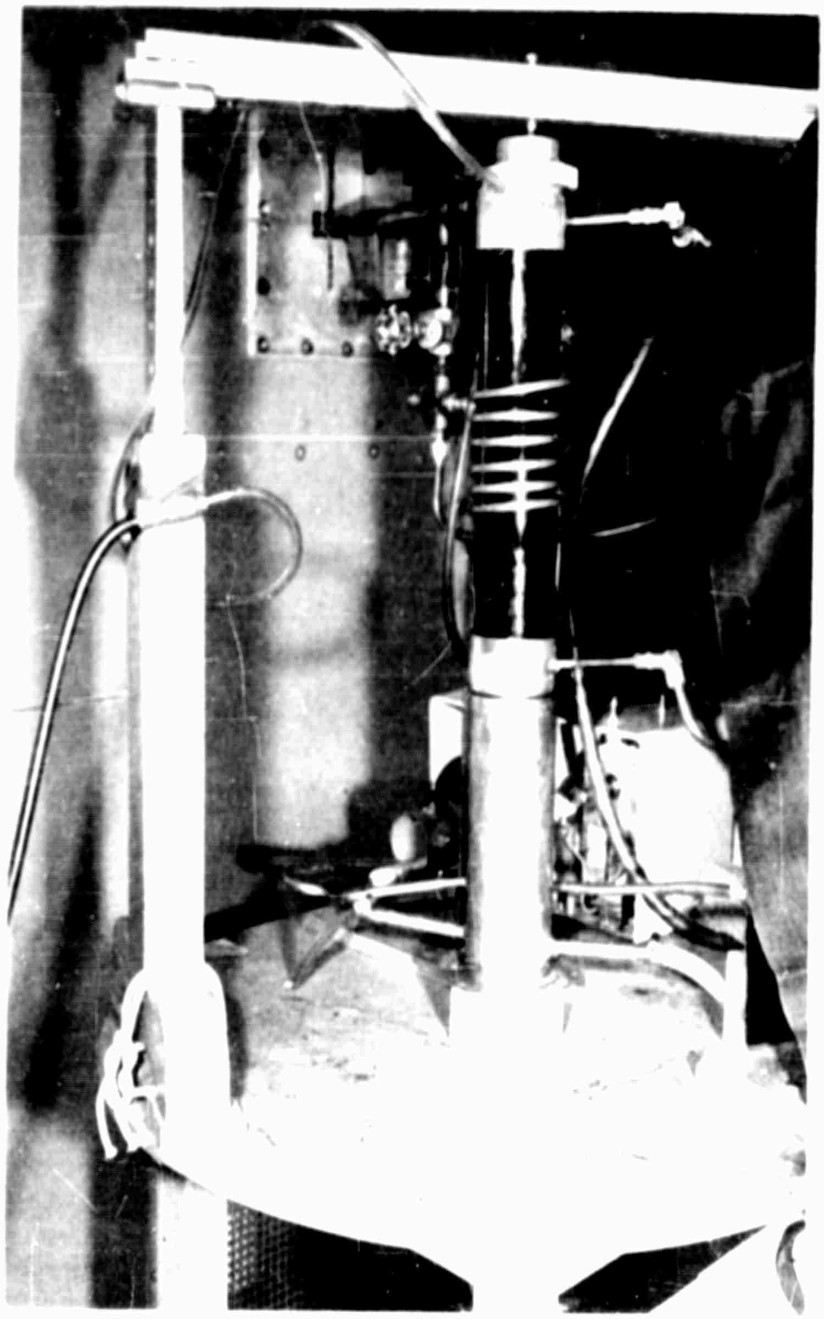


Fig. 2

Plasma-generator with black water coolant

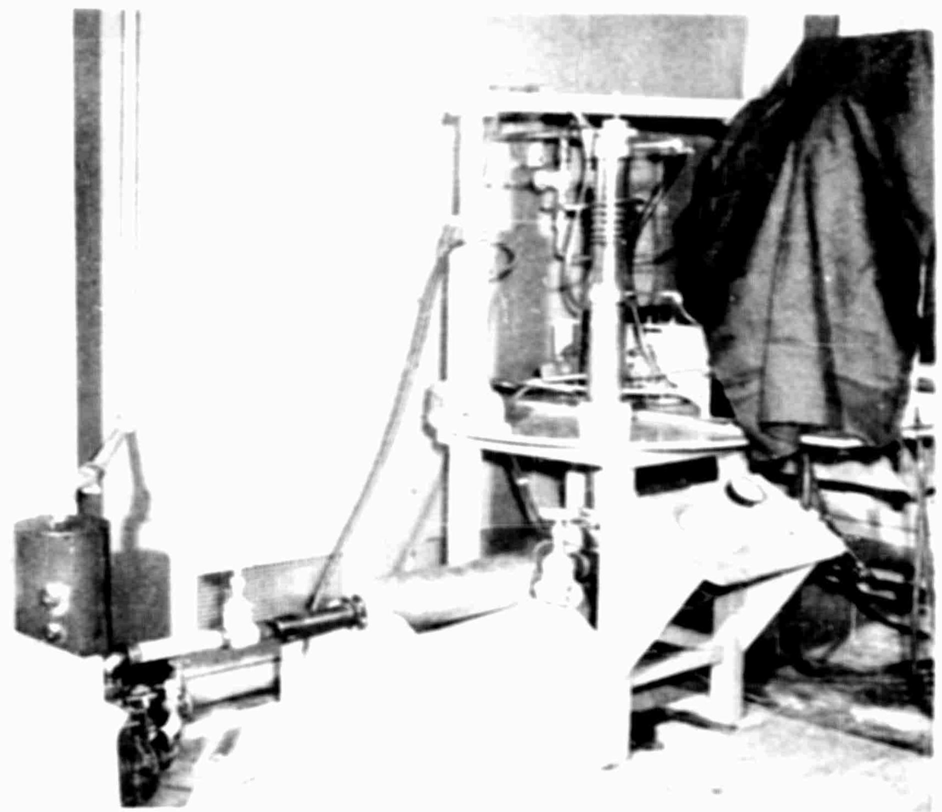


Fig. 3
Experimental apparatus

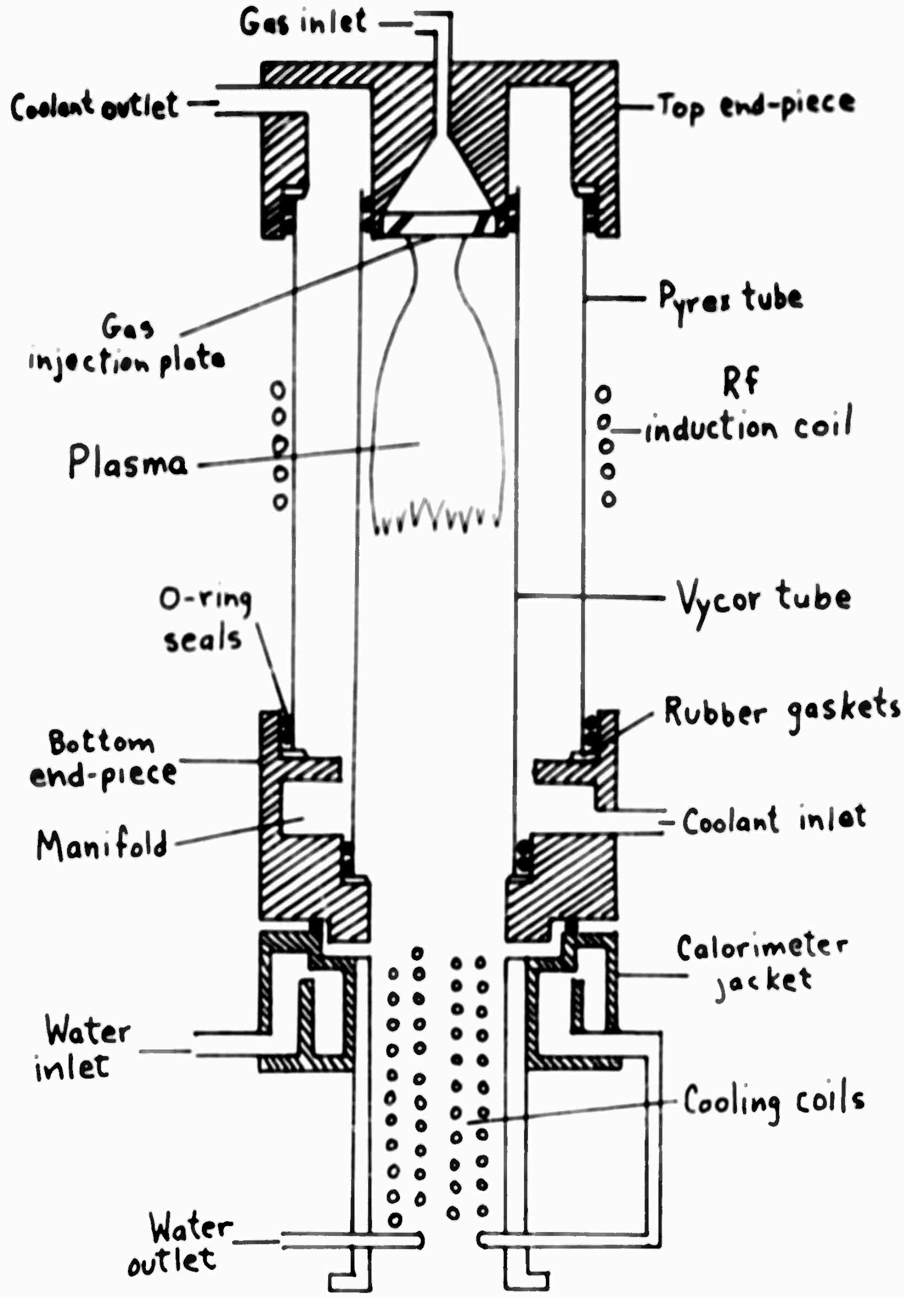


Fig. 4
Schematic of plasma-generator and calorimeter

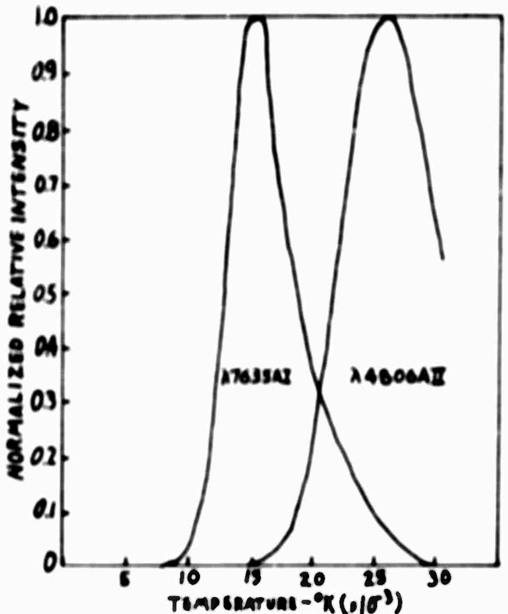


Fig. 5

(From Ref 1:617)

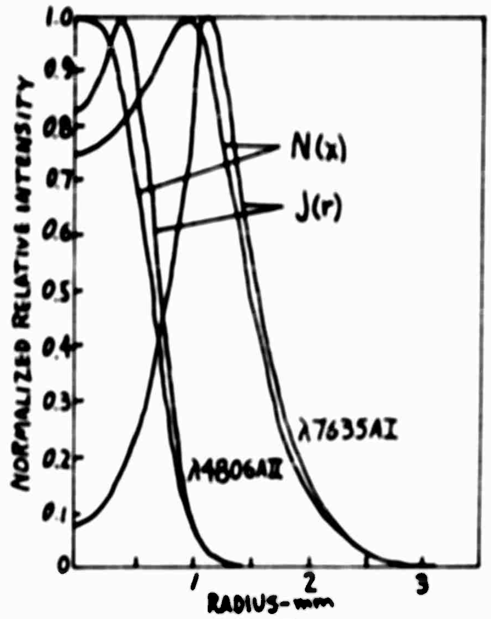


Fig. 6

(From Ref 1:616)

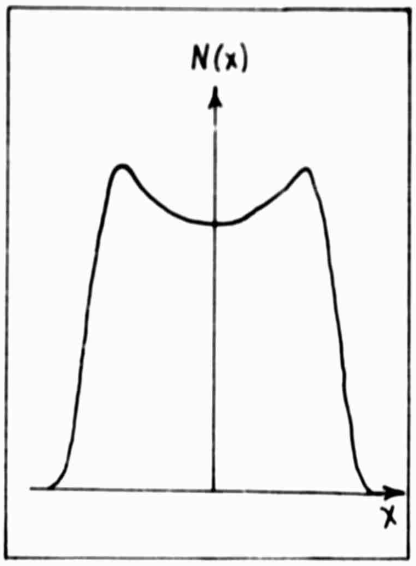


Fig. 7

Typical observed intensity of λ7635AI

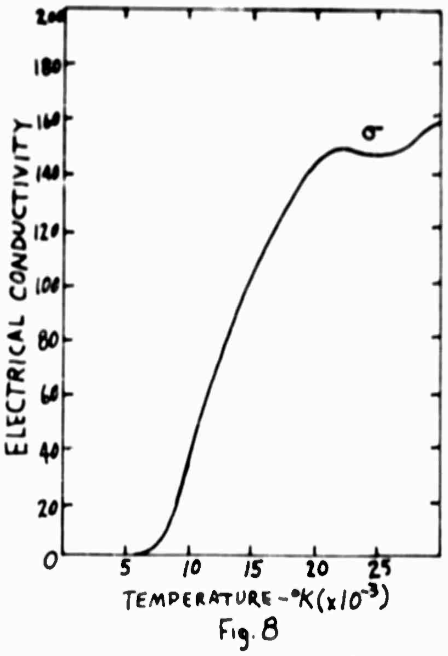


Fig. 8

(From Ref 1:620)

Fig. 9

Modified outer tube for Mode 3

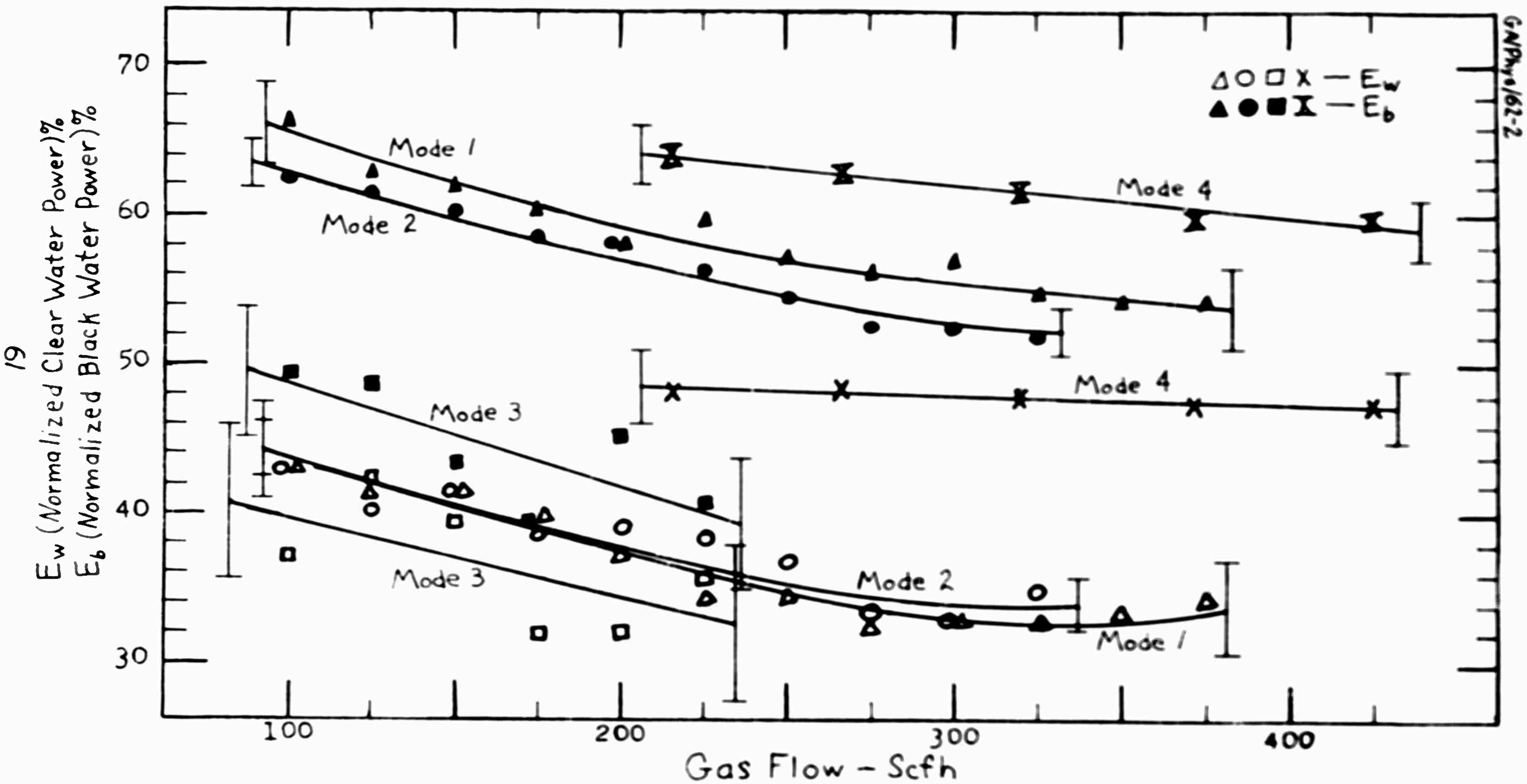

GA/Phys/62-2
Δ○□X — E_w
▲●■X — E_b
Mode 1
Mode 2
Mode 4
Mode 3
Mode 4
Mode 3
Mode 2
Mode 1
70
60
50
40
30
100
200
300
400
E_w (Normalized Clear Water Power)%
E_b (Normalized Black Water Power)%
Gas Flow - Scfh

Fig. 10

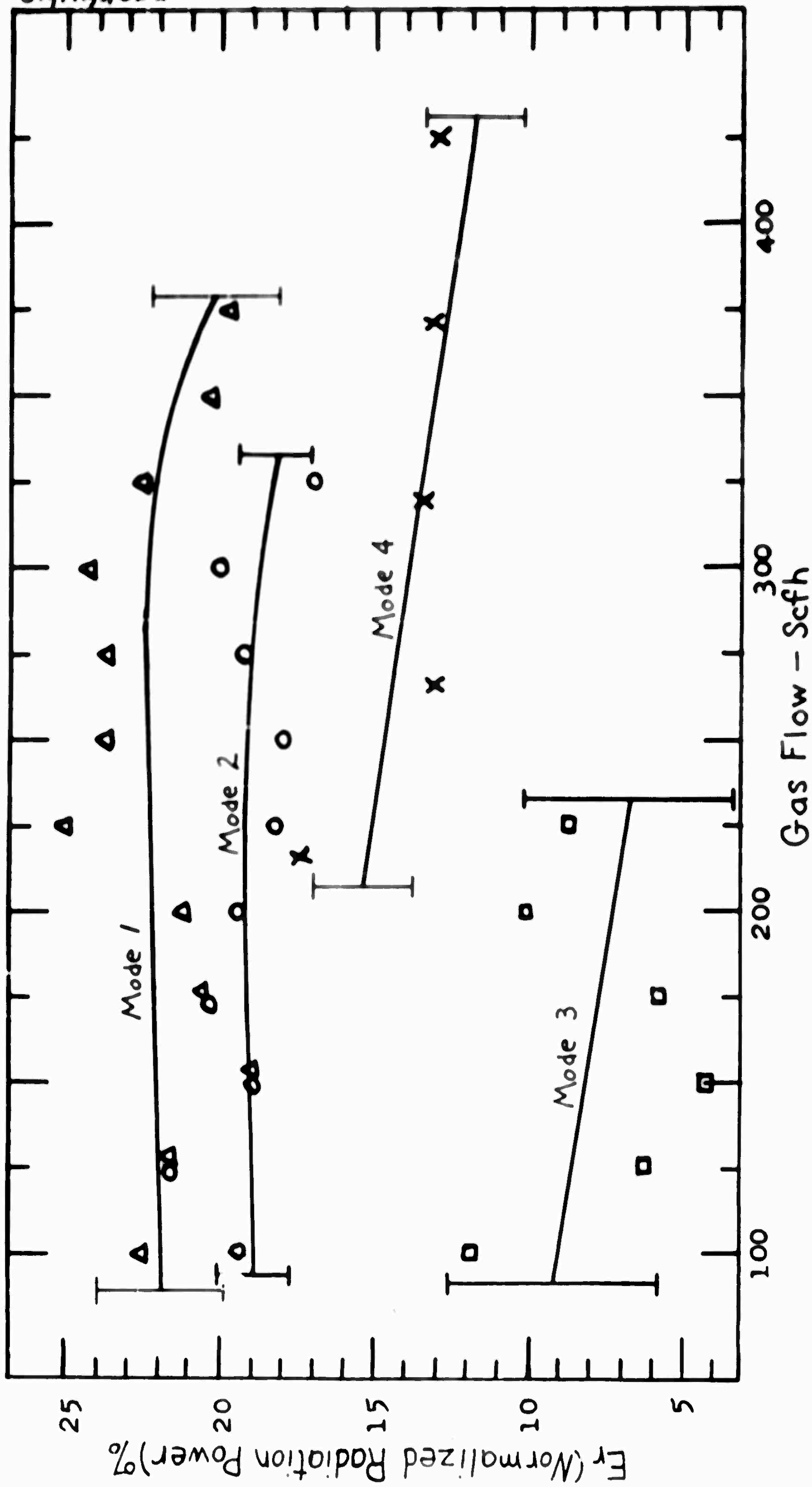
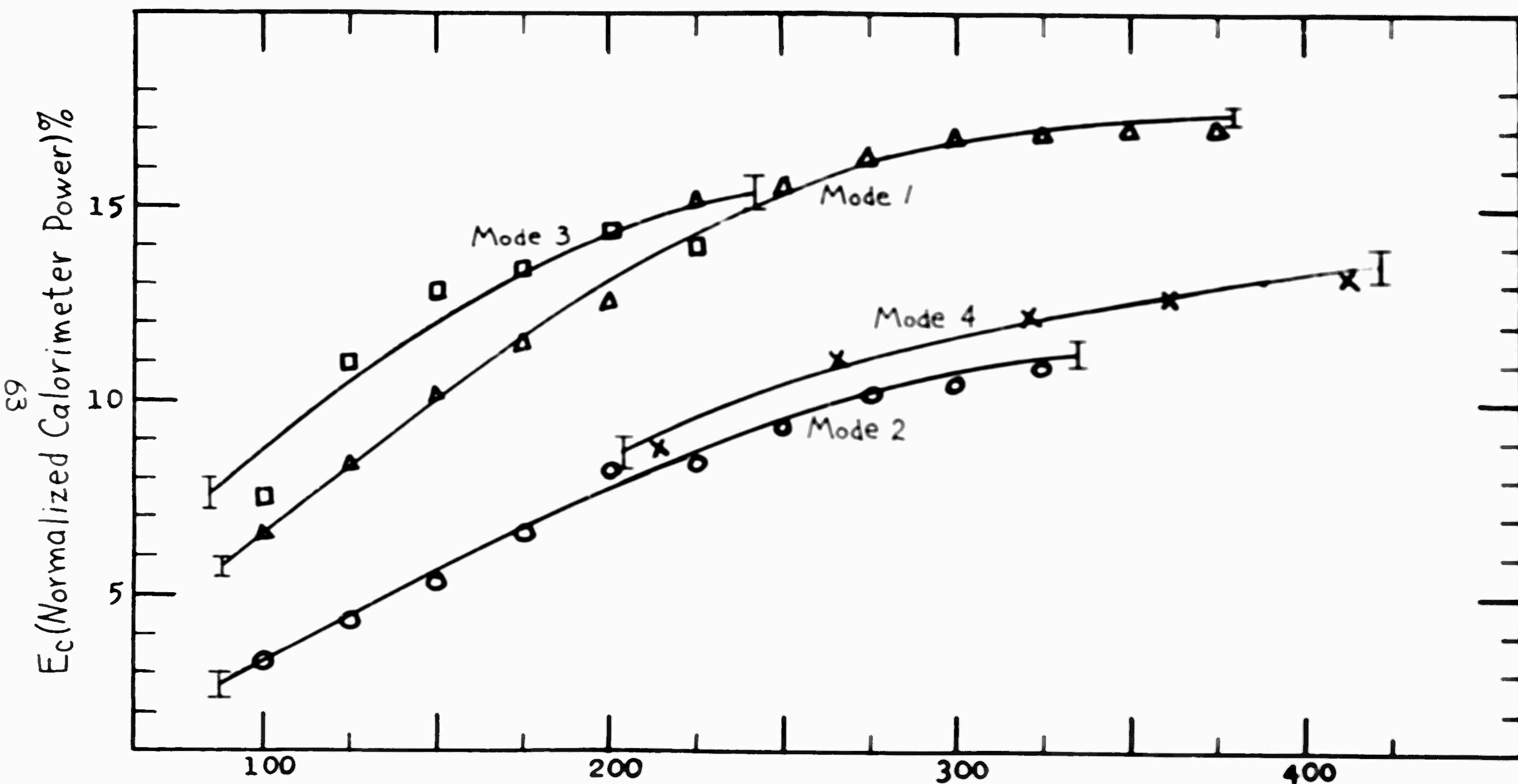

Mode 1
Mode 2
Mode 3
Mode 4
25
20
15
10
5
100
200
300
400
Er (Normalized Radiation Power)%
Gas Flow – Scfh

Fig. 11



Mode 3
Mode 1
Mode 4
Mode 2
15
10
5
100
200
300
400
E_c(Normalized Calorimeter Power)%
Gas Flow - Scfh

Fig. 12

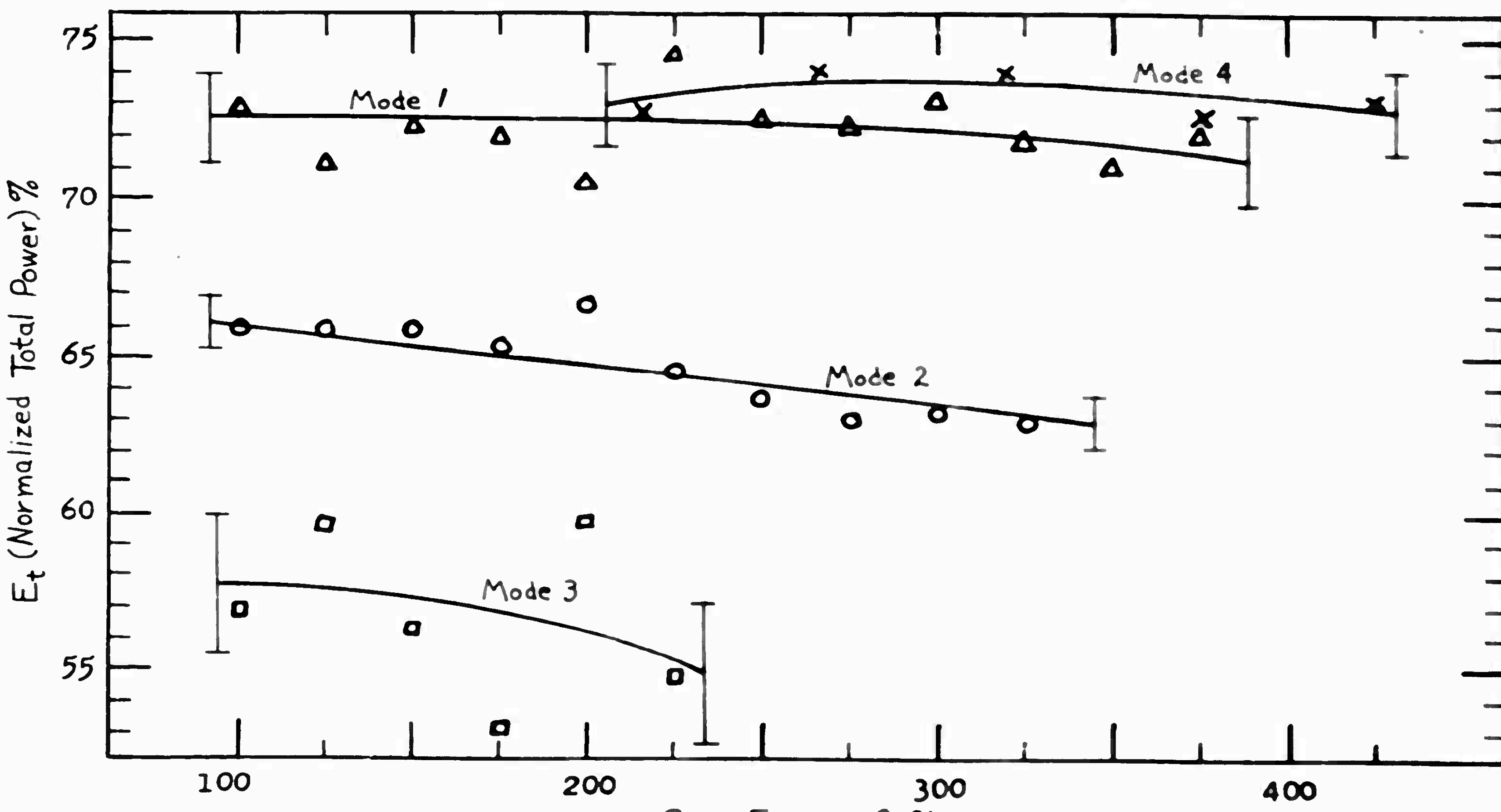

75
70
65
60
55
E_t (Normalized Total Power) %
100
200
300
400
Gas Flow – Scfh
Mode 1
Mode 2
Mode 3
Mode 4

Fig. 13

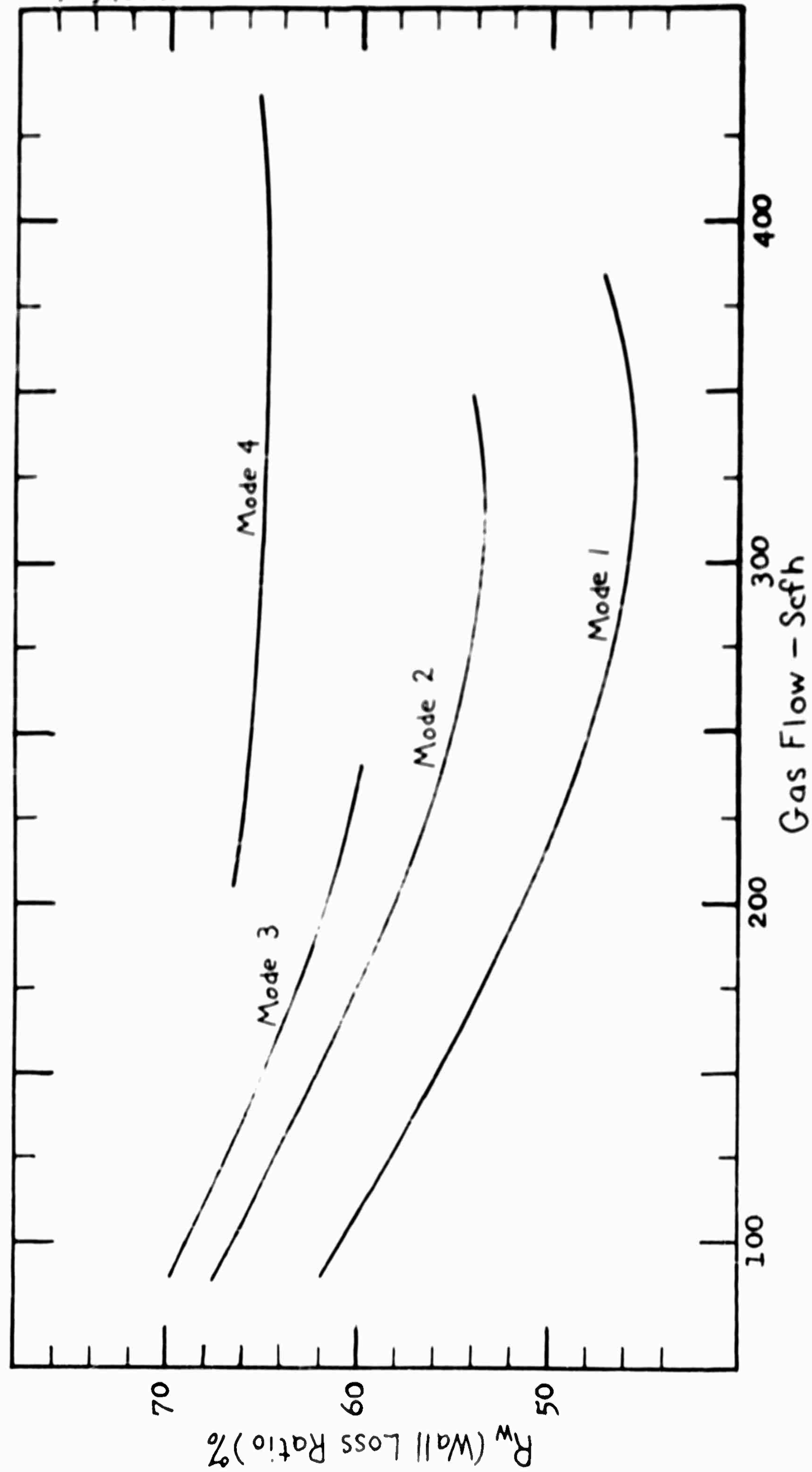

Mode 1
Mode 2
Mode 3
Mode 4
100
200
300
400
Gas Flow – Scfh
70
60
50
R_w (Wall Loss Ratio)%

Fig. 14

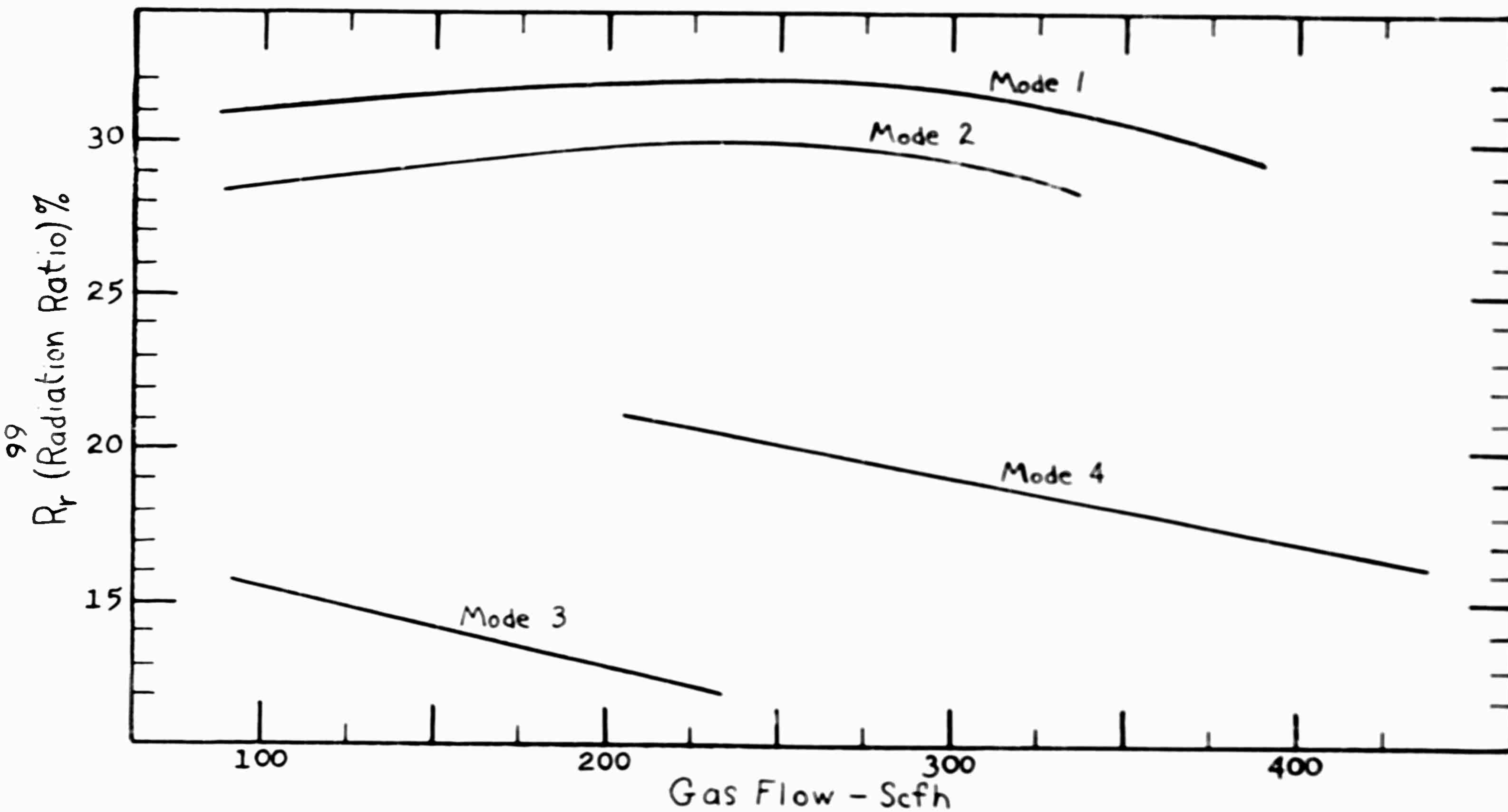

Mode 1
Mode 2
Mode 3
Mode 4
30
25
20
15
100
200
300
400
Gas Flow - Scfh
R_r (Radiation Ratio)%

Fig 15

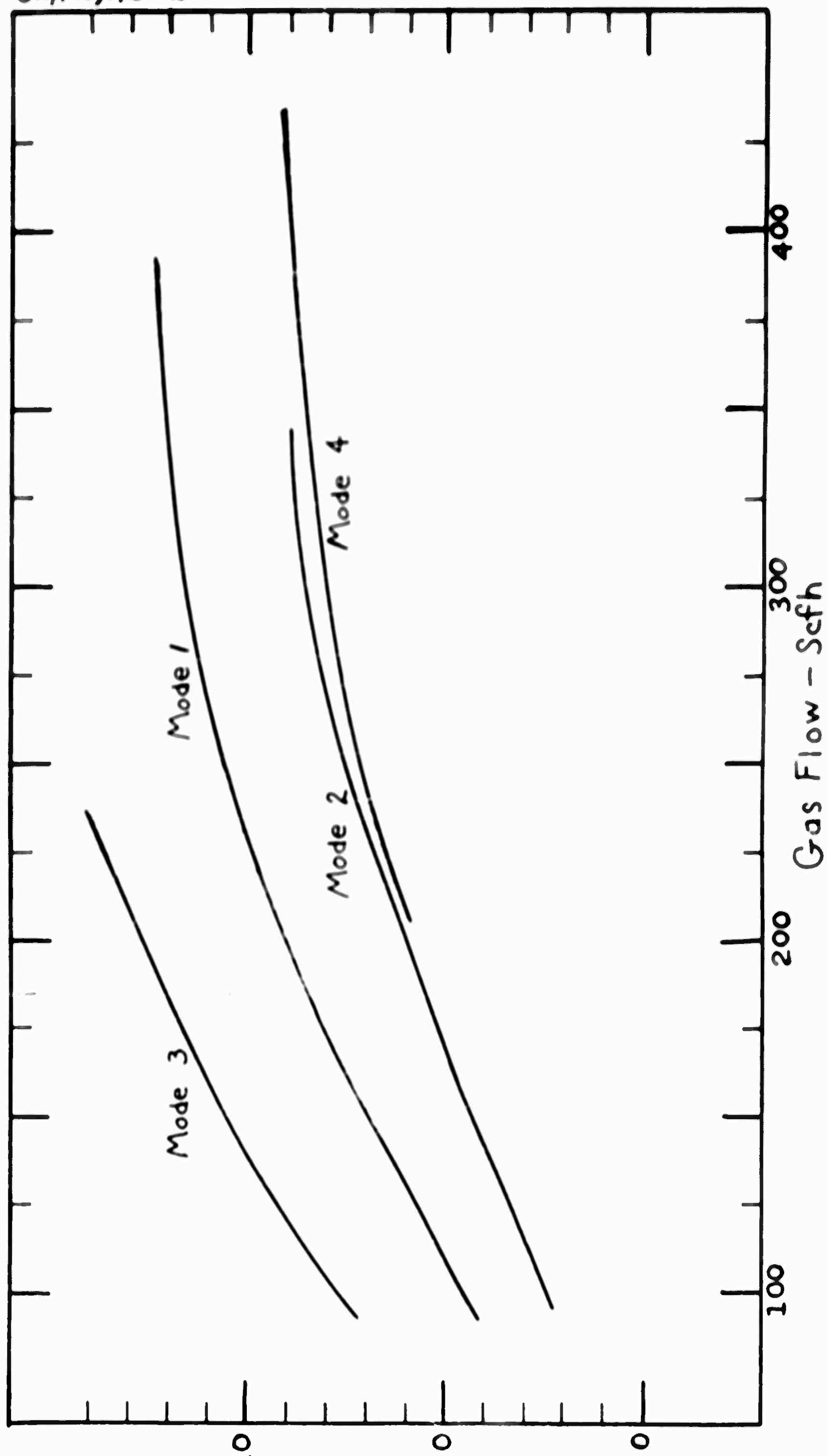

Mode 1
Mode 2
Mode 3
Mode 4
100
200
300
400
Gas Flow - Scfh
0
10
20
R_c (Calorimeter Ratio)%

Fig. 16

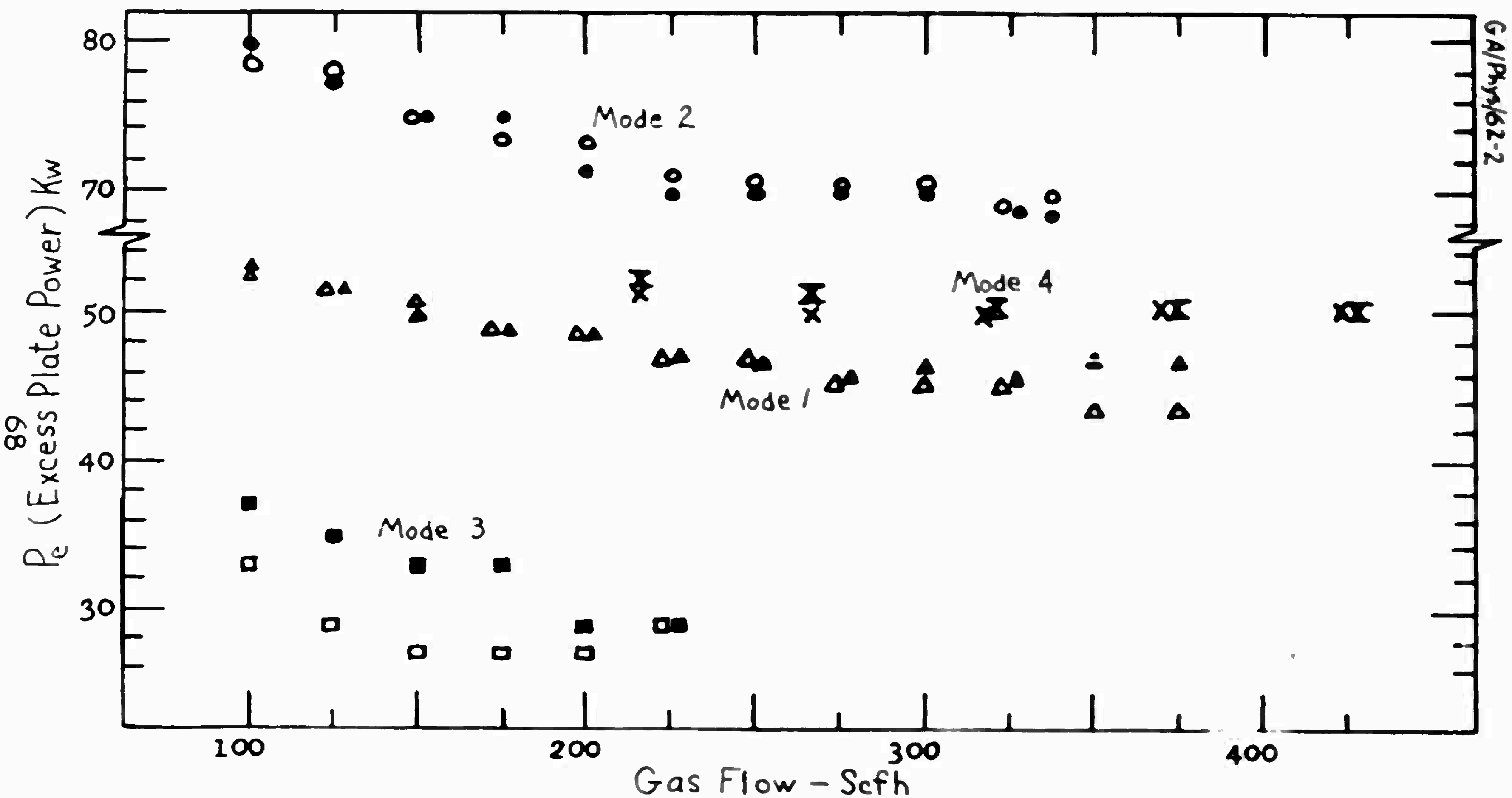

GA/Phys/62-2
Mode 2
Mode 4
Mode 1
Mode 3
80
70
50
40
30
P_e (Excess Plate Power) Kw
100
200
300
400
Gas Flow – Scfh

Fig. 17

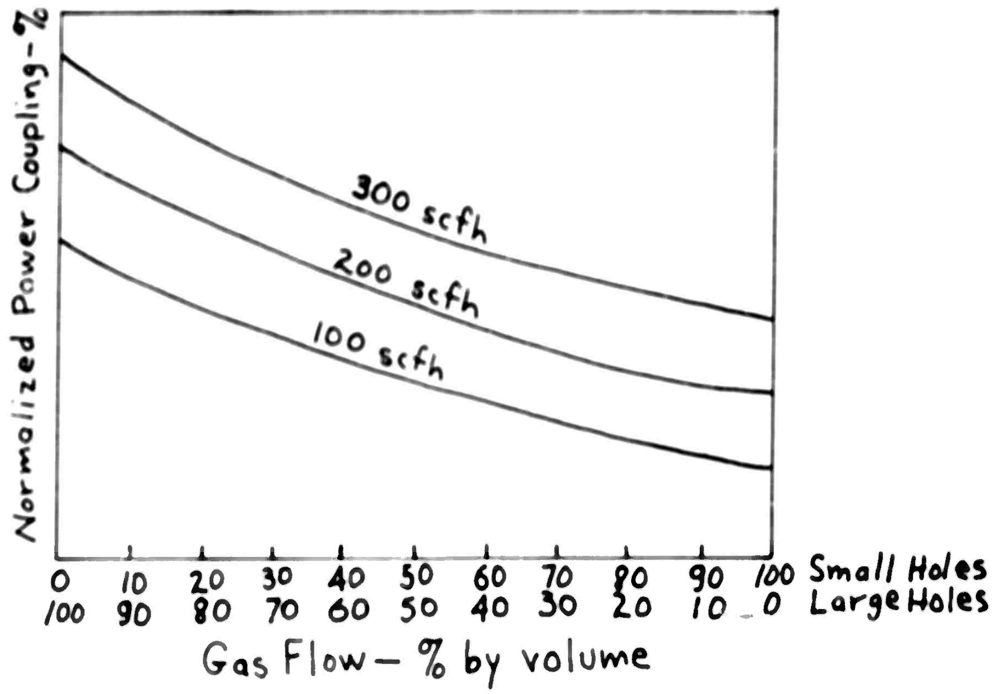


Fig. 18

Power coupling as a function of changing vortex strength, with excess plate power and total gas flow constant

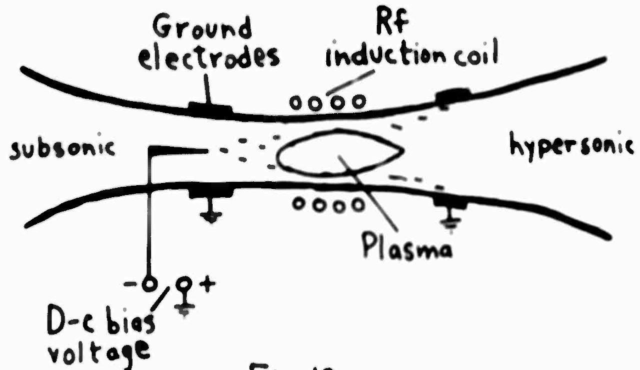


Fig. 19

Supersonic heating by induction-coupled plasma

Vita

Howard R. Cannon was born o [redacted] PII Redacted He graduated from Northeast High School in Kansas City, Missouri in 1947. In 194[illegible], he enlisted in the United States Air Force, and was appointed to the United States Military Academy from the Regular Air Force in June 1952. On [illegible] June 195[illegible], he was commissioned a Second Lieutenant in the Regular Air Force, and he graduated from the United States Military Academy on [illegible] June 195[illegible] with a Bachelor of Science degree in Military Science. Prior to admission to the Air Force Institute of Technology, he served as a missile operations officer in [illegible], Korea.

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PII Redacted